Integrated Sensor Analysis GRACE

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Summary. In this article performance estimates for the accelerometers, the star sensors and the K-Band ranging system onboard the GRACE satellites are given. It is shown that the accelerometers perform slightly worse than specified and that the star sensor and K-Band ranging system performances agree with the specifications. It is also demonstrated that mainly for the accelerometers performance assessment further investigations are needed as effects of unknown origin affect the measurements. For each instrument the results from the highrate L1a to the filtered and downsampled L1b data processing are shown and discussed. Concerning the accelerometer processing, good agreement with the data provided by JPL has been reached, concerning the star sensors and the K-Band system differences remain.

Key words: GRACE, sensor analysis, performance estimation, data processing

1 Introduction

The GRACE mission provides gravity field estimates with unprecedented accuracy. The complex and highly sophisticated sensor system onboard the GRACE satellites is responsible for this increase in quality. At the IAPG (Institute for Astronomical and Physical Geodesy) an integrated sensor analysis of the GRACE sensor system has been conducted during the last three years. A data set consisting of three days of data was used for the studies. Main fields of interest were:

- The derivation of mathematical models of the individual gravity relevant sensor systems of the GRACE satellites and the integration into a complete model that also allows to understand the interactions and couplings of the sensor systems
- The estimation of the sensor performance from real data, the comparison to the anticipated performance and the explanation of occurring differences
- The derivation of processing methods to high rate instrument data (called L1a data) to the level of low rate filtered 5s-data (called L1b data).

In this article performance estimates of the three key instruments of the GRACE mission, the accelerometer, the star sensor and the K-Band ranging system are derived and discussed. The processing of each instrument's data from high rate instrument data level to low rate filtered and downsampled level is briefly described. The results are compared to the data set provided by the JPL.

2 SuperSTAR Accelerometer

2.1 Performance Estimation

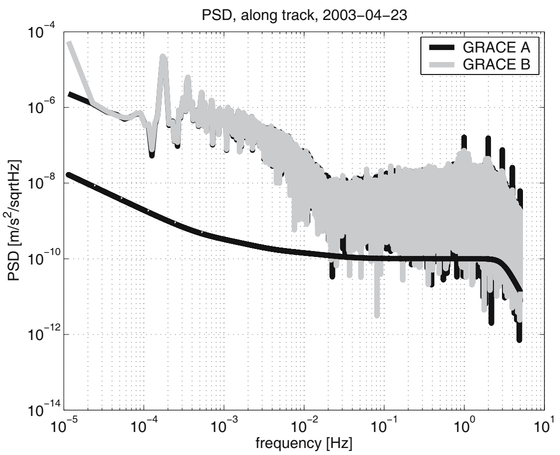

Fig. 1. Power Spectral Density (PSD) of the along-track component of the L1a accelerometer measurements of GRACE A & B

To investigate the performance of the linear acceleration measurements of the accelerometers onboard the GRACE satellites, only the raw data (L1a) is suited as the processed (L1b) data is treated with a low-pass filter that makes it impossible to estimate the high frequency noise. The accelerometers have two sensitive axes (along track and radial) and one less sensitive axis (cross-track). The low-frequency noise is not accessible through the analysis of a single accelerometer's measurements as the low-frequency noise is superposed by the measurement signal. The measurement signal are the non-gravitational accelerations acting on the satellites. At a certain frequency the signal to noise ratio become one and noise dominates the measurement. In Fig. 1 the comparison between the theoretical noise level and the apparent noise level of the real measurements is shown. Apparently the measurements of GRACE A and B show the same spectral characteristics, dominant frequencies are once and twice per revolution at about $2 \cdot e^{-4}$ Hz and $4 \cdot e^{-4}$ Hz. The signal decreases until at about $3 \cdot e^{-2}$ Hz it levels out into white noise. The level of this white noise is about a factor of 10 higher than the specified noise level for the accelerometers. A speciality of the GRACE A accelerometer are the prominent peaks on 1 Hz and multiples, their origin is unknown. Three possible causes of the higher noise level have been identified:

1. thrusterevents
2. twangs
3. spikes and peaks

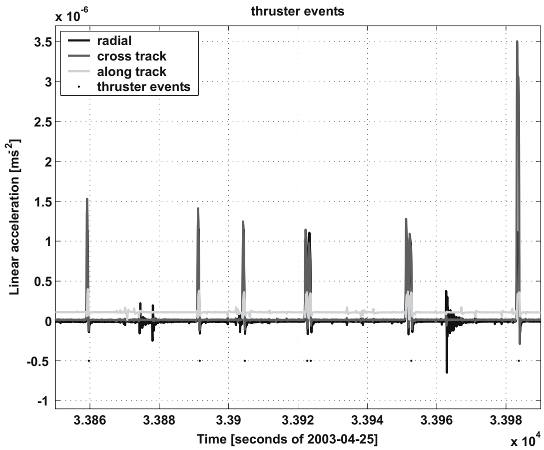

Fig. 2. Series of thruster events on GRACE A

Thrusterevents

A series of thruster events is shown in Fig. 2. Although the purpose of the thruster firings is to exert angular accelerations on the satellites, a thruster event also shows up in the measurement of the linear accelerations because of thruster misalignment and the displacement of the center of mass from the center of the proof mass of the accelerometer. The amplitudes range from 1 up to $3.5 \cdot e^{-6}$m/s^2. As the linear accelerations due to thruster misalignment are real linear accelerations acting on the satellites it is correct that they are measured and show up in the linear accelerations measurements. The measured linear accelerations due to the center of mass offset however have to be considered as errors in the measurement, as they represent no real linear acceleration acting on the satellites. For both satellites the center of mass offset is kept so small through mass trim maneuvers that this effect can be neglected. As during the periods of thruster events only the effects caused by the misalignment of the thrusters are measured, it is sensible to exclude periods of thruster events for the performance estimation.

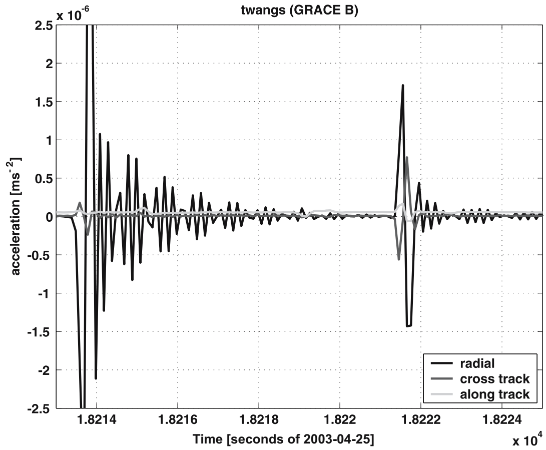

Fig. 3. Typical example of 'twangs' in the linear acceleration measurements

Twangs

Typical examples of a so called 'twang' are shown in Fig. 3. A twang is very similar to the reaction of a damped harmonic oscillator to a step impulse. It consists of an oscillation with decreasing amplitude, the typical duration is about 4 to 5 seconds (cf. (Hudson, 2003)). The amplitudes reach over $3 \cdot e^{-6}\mathrm{m/s}^2$. It is assumed that the reason for the twangs is the flattering of a thin foil on the bottom of the GRACE satellites, that could explain the massive occurrence in the radial component of the linear accelerations. Another possible reason is that they are a feature of the SuperSTAR accelerometer. If the latter was true, the twangs would have to be added to the error budget. If the twangs are caused by the foil, they are real non-gravitational accelerations acting on the satellites and these periods should be excluded from the performance estimation.

Peaks and Spikes

The third effect that adds to the apparent noise level are regular peaks and spikes occurring in all three components of the linear accelerations. A typical example is shown in Fig. 4. The peaks consist of a deflection from the mean in an arbitrary direction, followed by a deflection with a magnitude of one third of the original one in the opposite direction (cf. (Flury, 2004)). The amplitude reach a level of about $1 \cdot e^{-7}$ m/s^2 for the along-track component and $1 \cdot e^{-8}$

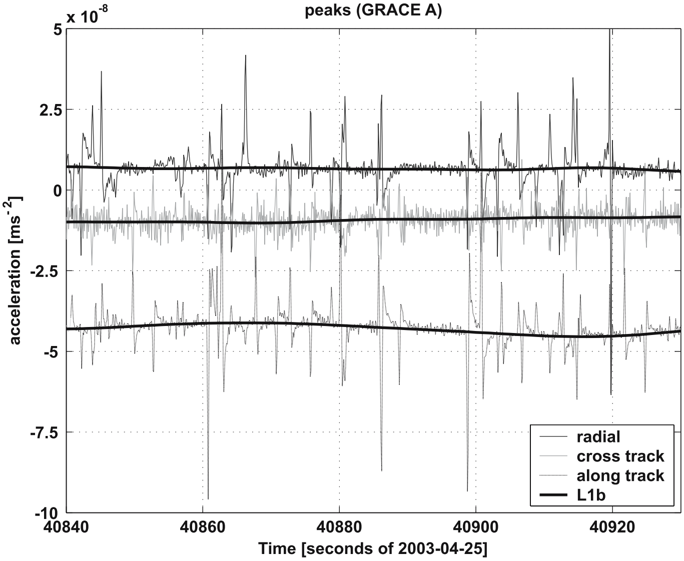

Fig. 4. Typical example for the spikes and peaks affecting the linear acceleration measurements

m/s^2 for the cross-track and radial components. Regarding the L1b data it seems that the effect is completely removed by the applied low-pass filter, however it is unclear if low-frequency effects remain in the filtered data. As the peaks and spikes are regular, it is assumed that they are a feature of the accelerometer.

Performance Assessment

The performance of the accelerometer was assessed in two ways:

1. Analysis of undisturbed periods of single accelerometer data
2. Spectral analysis of the difference of the accelerometer measurements of both satellites during undisturbed periods using L1b and L1a data.

Analysis of the signal of a single accelerometer

For the analysis of the single accelerometer data, only periods without thruster events, twangs or peaks have been used. According to (Flury, 2004) the following standard deviations are derived for undisturbed periods:

$$\text{along-track } 3 \cdot e^{-10}\text{m/s}^2$$
$$\text{cross-track } 7 \cdot e^{-10}\text{m/s}^2$$
$$\text{radial } 2.1 \cdot e^{-10}\text{m/s}^2$$

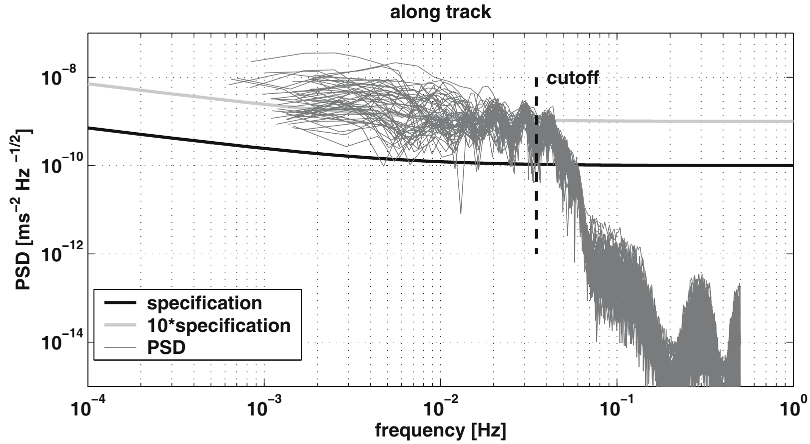

Fig. 5. PSD of differences of L1B accelerometer data between GRACE A and B during thruster free periods

Comparing this with the specifications given in (Stanton et al., 1998), the following conclusions can be drawn:

1. the noise level of the along-track and the radial component is about 2-3 times higher than the specified level of $1 \cdot e^{-10}$ m/s^2.
2. the noise level of the cross-track component is about 70% of the specified noise level of $1 \cdot e^{-9}$m/s^2.

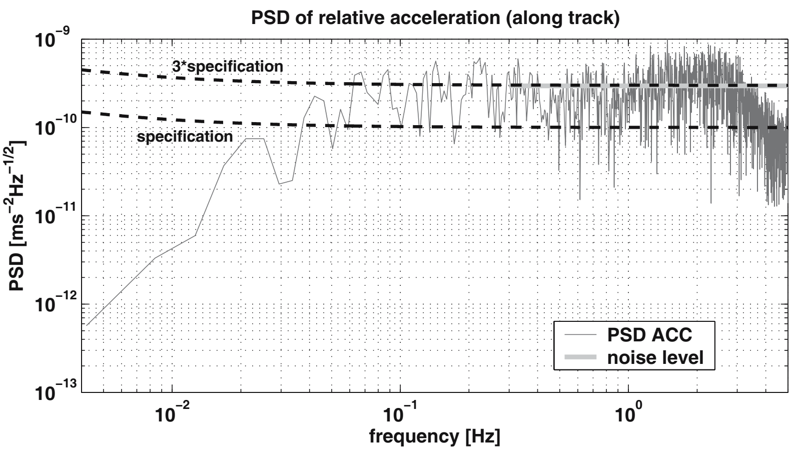

Fig. 6. PSD of differences of L1a accelerometer data between GRACE A and B during periods free of thruster events, twangs and peaks

Analysis of the differences between accelerometer measurements

The GRACE mission with its identical twin satellites offers the unique possibility to assess the performance of its accelerometers by using their redundancy: due to the orbit configuration, the trailing satellite arrives after about 27 s at the same location as the leading one. During this short time the atmosphere does not change significantly, thus the accelerometer measurements should be comparable. The difference between to accelerometer measurements includes the following effects:

- errors in the attitude information of both satellites
- scale factors and higher order error terms
- the sum of the measurement noise of both satellites

Figure 5 shows the PSD of the difference of L1b accelerometer measurements. Only periods without thruster events were used, but periods with twangs and peaks were not excluded to get longer timer series to eventually assess an upper limit of the low frequency part of the accelerometers noise. The differences fit well to an upper limit of 10 times the specification. The analysis of longer periods would yield more exact results, but because of the frequent thruster firings this is not possible.
In Fig. 6 the difference PSD of L1a accelerometer measurements is shown. Here periods without thruster events, twangs or peaks were used. The difference is following an error model that is three times above the specification. This analysis confirms the findings from the analysis of the single accelerometer measurement data analysis.
Comparing these results with the specifications given in (Stanton et al., 1998), the following conclusions can be drawn:

1. the noise characteristics of the accelerometer on GRACE A and B are very similar.
2. the noise level of the along-track and the radial component is about 2-3 times higher than the specified level of $1 \cdot e^{-10}\mathrm{m/s}^2$.

2.2 L1a to L1b Data Processing

The processing of the accelerometer data from L1a to L1b data has been conducted in accordance with (Wu and Kruizinga, 2004). Initial differences were reported to JPL where they helped to discover a glitch in the official processing software that led to the replacement of 30% of the data with interpolated values. The differences between IAPG and JPL processing results are now on the level of numerical accuracy. The effects of the strategy of the JPL to apply a low pass filter of 35 mHz to the accelerometer data instead of the same filter as used for the downsampling of the K-Band data should be investigated. It is unclear how the various effects like twangs, spikes and thruster events should be treated correctly. Although the applied low-pass filter removes the major effect of them, it should be investigated if long-term effects remain.

3 Star Sensor

3.1 Performance Estimation

The star sensor measurements are polluted by mainly white noise, not colored noise as the accelerometer. The orientation is derived from pictures taken of the sky in the field of view of the star tracker. The orientation w.r.t. an inertial system is derived by comparison with a star catalogue. The elements of the orientation matrix, which is basically a rotation matrix, can not be measured with an homogeneous accuracy: rotations about the line of sight of the star tracker are measured with an accuracy about 8 times worse the accuracy of rotations perpendicular to the line of sight of the star trackers (cf. (Wu and Kruizinga, 2004) and (Stanton et al., 1998)). Figure 7 shows the PSD of the

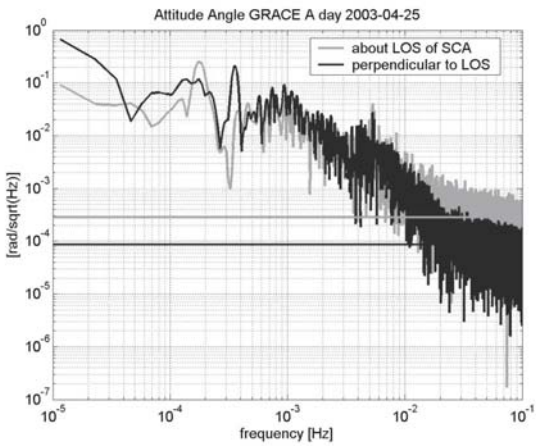

Fig. 7. PSD of attitude angles of GRACE A in star sensor reference frame. The horizontal lines show the estimated level of the white measurement noise

attitude angles of GRACE A. The estimated noise level for the rotations perpendicular to the line of sight is about $1 \cdot e^{-4}$ rad/$\sqrt{\text{Hz}}$ which is about three times the specification of $3 \cdot e^{-5}$ rad/$\sqrt{\text{Hz}}$. The noise level for rotations about the line of sight is about $2 \cdot e^{-4}$rad/$\sqrt{\text{Hz}}$ which agrees well with the specification of $2.4 \cdot e^{-4}$ rad/$\sqrt{\text{Hz}}$. Figure 7 shows the PSD of the attitude angles of GRACE B. The estimated noise level for the rotations perpendicular to the line of sight is about $3 \cdot e^{-5}$rad/$\sqrt{\text{Hz}}$ which agrees well with the specification. The noise level for rotations about the line of sight is about $2 \cdot e^{-4}$rad/$\sqrt{\text{Hz}}$ which also agrees well with the specification of $2.4 \cdot e^{-4}$ rad/$\sqrt{\text{Hz}}$.
The following conclusion concerning the star sensor performance can be drawn:

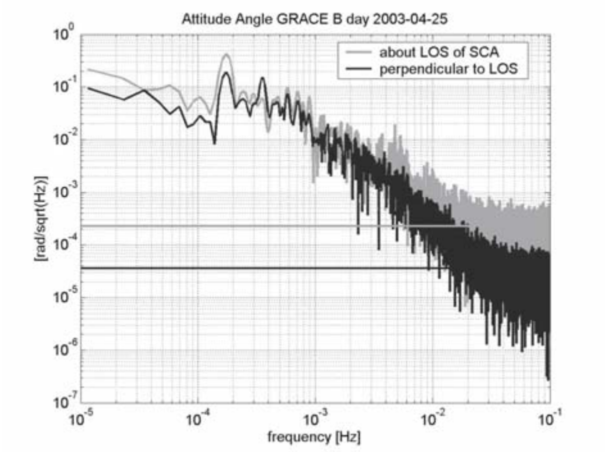

Fig. 8. PSD of attitude angles of GRACE B in star sensor reference frame. The horizontal lines show the estimated level of the white measurement noise

- The star sensor on GRACE A performs slightly worse than the star sensor on GRACE B concerning the rotation perpendicular to the line of sight.
- The performance of the star sensor on GRACE B agrees well with the specification.
- The performance of the star sensor on GRACE A concerning the orientation perpendicular to its line of sight is about three times worse than the specification. The performance concerning the rotation about its line of sight agrees well with the specifications.

3.2 L1a to L1b Data Processing

Onboard each GRACE satellite two star cameras are available for attitude determination. Apart from sun or moon intrusions the star sensors operate in dual mode, i.e. it is possible to combine the data of the two sensor heads. The combination takes into account that the quality of the derived rotation about the line of sight of the sensor heads is worse than the quality of the rotation derived perpendicular to the line of sight (from (Wu and Kruizinga, 2004)):

$$\mathrm{Q_{comb}} = Q_1 \cdot (1, \mathrm{M}\varDelta_{12}) \tag{1}$$

where:

$$\mathrm{M} = \frac{1}{2} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & -\lambda \\ 0 & -\lambda & 1 \end{pmatrix} \tag{2}$$

$\lambda = \frac{\kappa^2-1}{\kappa^2+1}$ and $\kappa = 8$ taking into account that the attitude information for rotations about the line of sight of the star trackers is about eight times worse

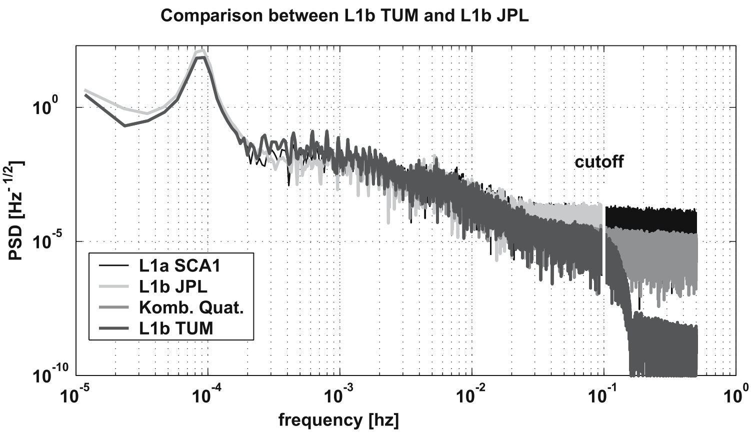

Fig. 9. Comparison of the L1b Data provided by JPL and the L1b data generated at IAPG. Differences are noticeable. It is interesting that the combined solution from JPL shows no effect of smoothing but the solution from IAPG does

than for rotations perpendicular to the line of sight. Δ_{12} is the observed difference between the two sensor heads. Basically the combination is a weighted mean. Figure 9 shows a comparison of the L1b star sensor data derived at IAPG and the star sensor data provided by JPL. Significant differences on all frequencies are noticeable. It is interesting that the spectrum of the combined quaternions from JPL on L1b compared to L1a shows no significant difference. In contrast the L1b quaternions derived by IAPG show smoothing effects visible as a lower noise level towards the higher frequencies. A possible explanation for this effect is that probably for the derivation of the JPL data a different value for κ was used. Taking a closer look at the differences in Fig. 10 reveals that the differences are small except from certain spikes appearing in a regular pattern. Closer investigation shows that these epochs are epochs where the star sensor switches from dual to single head operation. More detailed investigations are needed to identify the reasons for these deviations.

4 K-Band

The measurements of the K-Band ranging system are affected by two kinds of noise:

1. the instability of the local oscillator
2. the phase noise of the measurements

As Fig. 11 shows, the error source 1 can be avoided if GPS timing is used, which is the case for the K-Band processing. Towards the lower frequency the

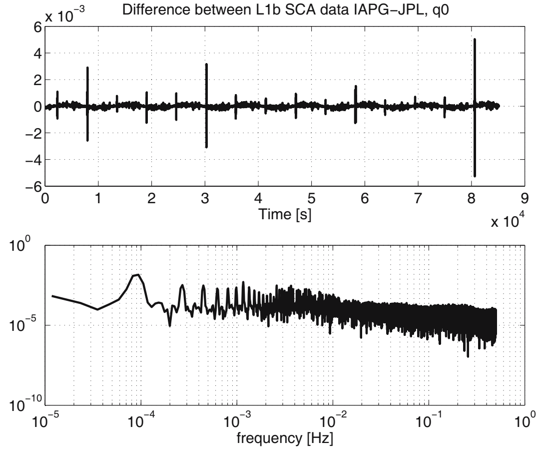

Fig. 10. Difference between IAPG derived L1b star sensor data and the data provided by the JPL

error is dominated by the inaccuracy of the synchronization of the measurements from both satellites, which shows up as a drift. Towards the higher frequencies the error is dominated by white noise with an magnitude of 1 micron. The range measurement is the original measurement, the range rate and the range acceleration are derived from the range via differentiation. The noise model is extracted from (Thomas, 1999). Figure 12 shows the PSD of

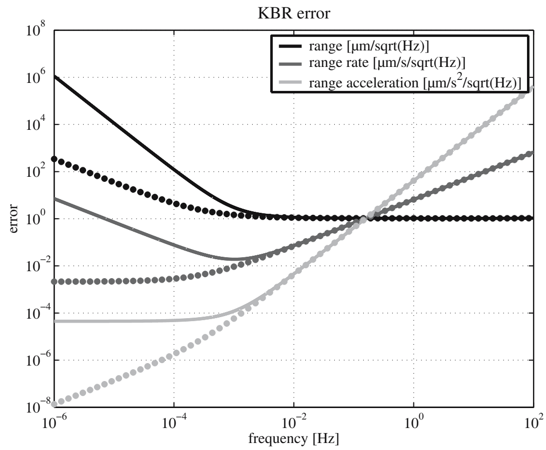

Fig. 11. PSD of theoretical K-Band measurement errors. The solid lines represent the error if the timing from the Ultra Stable Oscillators (USO) is used, the dotted lines represent the error if GPS timing is used. For the GRACE KBR data processing GPS timing is used

the L1b range measurement. Prominent peaks are on the once and twice per revolution frequencies. The signal decreases until at about $2.5 \cdot e^{-2}$Hz noise dominates the signal. Note that the noise is not white, it is colored as the range rate signal is shown. The dashed line represents the specified error psd. The level of the noise agrees well with the specified error level. Is is about 2 μm/s/$\sqrt{\text{Hz}}$. Note the peaks on $4.5 \cdot e^{-2}$ Hz and multiples. Their origin is unknown, it could be correlated with the peaks observed in the accelerometer measurements on GRACE A.

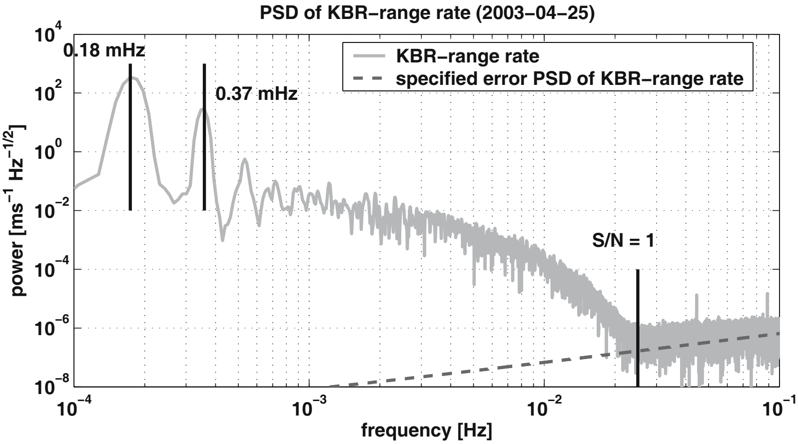

Fig. 12. PSD of KBR range rate signal and specified error level

4.1 L1a to L1b Data Processing

Again the processing was conducted according to (Wu and Kruizinga, 2004). Figure 13 shows the difference between the range rate derived at IAPG and the range rate provided by JPL. The difference is significant. It has a sinusoidal form, the dominant frequencies are once per revolution and multiples. The amplitudes reach the level of about 2 μm/s, about twice the specified noise level. Further investigations are needed to determine the reason for the difference, a first guess would be differences in the time tagging, resp. the derivation of the clock correction for the onboard time, as even a small phase shift could lead to the difference that has been derived. It seems that numerical problems can be excluded, as the difference shows a regular structure, and doesn't behave irregularly due to round-off errors.

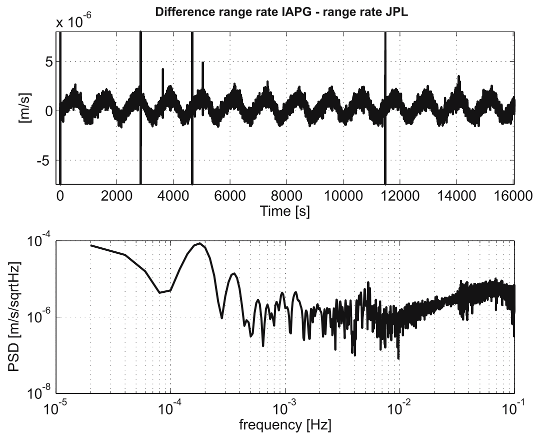

Fig. 13. Difference between the Range Rate derived at IAPG and the Range Rate provided by JPL

5 Conclusions and Outlook

Concerning the performance assessment of the sensor system the following conclusions have been derived:

1. SuperSTAR accelerometers:
   - the noise level of the along-track and the radial component is about 2-3 times higher than the specified level of $1 \cdot e^{-10}$ $m/s^2/\sqrt{Hz}$.
   - the noise level of the cross-track component is about 70% of the specified noise level of $1 \cdot e^{-9} m/s^2/\sqrt{Hz}$.

   The given noise levels are derived from periods without twangs, peaks or thruster events.
2. Star sensors:
   - The star sensor on GRACE A performs slightly worse than the star sensor on GRACE B concerning the rotation perpendicular to the line of sight.
   - The performance of the star sensor on GRACE B agrees well with the specification (30 μrad/$\sqrt{Hz}$ relative to line of sight (LOS) and 240 μ rad/$\sqrt{Hz}$ around LOS).
   - The performance of the star sensor on GRACE A concerning the orientation perpendicular to its line of sight is about three times worse than the specification. The performance concerning the rotation about its line of sight agrees well with the specifications.
3. K-Band Ranging System
   - The performance of the range measurements agrees well with the specifications of 1 μm /$\sqrt{Hz}$.

Concerning the L1a to L1b data processing the following status has been reached:

- The results from the processing of the accelerometer data agree well with the results provided by JPL
- Concerning the Star Sensor processing, significant differences remain to be investigated.
- The results from the K-Band ranging system show large discrepancies compared to the noise level of the K-Band measurements (about a factor of 1e3 higher on range level and a factor of 2 on range rate level) The reasons for this discrepancies have to be investigated.

Outlook

The following future studies are planned:

- Accelerometers:
  1. Investigation if the twangs and peaks that show up in the accelerometer measurements are caused by real physical accelerations on the satellites or if they are a feature of the accelerometers
  2. Investigation of the effect of different low-pass filters to be applied for the downsampling from L1a to L1b.
- Star Sensors:
  1. Investigation of different strategies for the combination of the observations from the two sensor heads of each star sensor.
  2. Investigation of the possibility to combine star sensor measurements with accelerometer measurements.
  3. Investigation of the reasons for the differences in the L1b data derived by IAPG and the data provided by JPL.
- K-Band-Ranging System:
  1. Investigation of the reasons for the differences in the L1b data derived by IAPG and the data provided by JPL.

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