Comparison of the LaCoste & Romberg gravimeter ET18 with the superconducting gravimeter CD-034 at the Geodynamic Observatory Moxa (Germany)

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Abstract

Superconducting gravimeters were developed to overcome mechanical deficiencies of spring gravimeters. They are well known for their long-term stability. But what about the information contents in the other period ranges (short period and Earth tidal bands) compared to spring gravimeters?

For comparative analyses the well calibrated superconducting gravimeter CD-034 (SG) and the LaCoste and Romberg (L&R) Earth tide gravimeter ET18 record next to each other at the broadband Geodynamic Observatory Moxa (Germany). The processing and analyses of the one year long time series were carried out in three frequency ranges: the low frequency band ($< 1.5 \cdot 10^{-3}$ cph), the high frequency band (> 0.125 cph) and the Earth tide frequency intervals in between. Results are: same information content of both records in the high frequency band and the Earth tide frequency intervals, although the ET18 shows a higher noise level than the SG data. As expected, the ET18 time series contain a stronger instrumental long-term drift than the SG record.

The aim of this work is to evaluate the differences between the two data sets in the three frequency bands, and to calibrate the L&R with regard to the SG in order to prepare future measurements of the ET18 in other places.

1. Introduction

The sensors of the LaCoste & Romberg gravimeter ET18 (L&R) and the superconducting gravimeter CD-034 (SG) are totally different: The ET18 has a classical system with a mass at the end of beam which is supported by the zero-length spring (Asch et al. 1986b), whereas the SG has a small ball floating on a magnetic field produced by a superconducting coil system. Consequently, the data sets contain different information, and resolution of small signals (e.g. seasonal hydrological effects) is also different.

The L&R gravimeter ET18 was completed in 1975. It was used at different places in Germany (Asch et al. 1986a), Denmark (Jahr 1989), Fennoscandia (Jentzsch 1986, Weise 1992, Weise et al. 1999) and Greenland (Jentzsch et al. 1995, Ramatschi 1998). Aims of the measurements were comparative analyses of different gravity observations with regard to Earth tides and ocean tidal loading, and the comparison with the modelled response of the elastic Earth's crust. The gravimeter was calibrated several times at the vertical base-line in Hanover between 1985 and 1997 (Melzer 1989, Ramatschi et al. 1993).

Since April 1999 the SG records at the Geodynamic Observatory Moxa (Germany). The gravity registration consists of a dual-sphere-sensor system with high long-term stability. Aims of previous measurements were investigations of polar motion, core modes, Slichter triplet, Earth tides and free modes of the Earth (Kroner et al. 2004). Furthermore, comparative analyses of gravity residuals from the gravimeter to modelled effects of different hydrological contributions from soil moisture, water level, meteorological observations and snow were carried out (Kroner et al. 2007). The calibration factors of the superconducting gravimeter were determined twice a year parallel recordings of 2-3 days of an absolute gravimeter. The calculations of the calibration factors were carried out using the least squares method (Kroner 2002).

In previous studies, comparative analyses between superconducting gravimeters and mechanical spring gravimeters were also performed by other authors. By Richter et al. (1995), a report about the comparison of the spectra of 57 day parallel records from the SG-102 and the ET19 at the Black Forest Observatory (BFO, Germany). Another study concerned the differences between the L&R gravimeter ET19 at BFO, an identical instrument at the South Pole and the superconducting gravimeters at Brussels and Bad Homburg (Zürn et al. 1991).

New results in this paper are based on the following facts: The SG works with a dual-sphere-sensor system, and both gravimeters (the SG and the ET18) record next to each other in the Geodynamic Observatory Moxa, and for the comparison in different frequency bands time series of one year were used. The aim of these investigations is to test and classify the "old" L&R gravimeter ET18 for future use in other stations.

2. Fundamentals and techniques

At the broadband Geodynamic Observatory Moxa both gravimeters are operating under very stable conditions in a separate room. Moxa is located about 30 km south of Jena. The observatory is built in a narrow valley and contains of rooms converted by soil to reduce environmental noise. The galleries inside the hill are used for strain measurements and seismic observations. The Observatory Moxa is well known for its low noise level compared to other stations of the Global Geodynamic Project all over the world. The scale is the New Low Noise Model of Peterson (1993), from the seismic to the tidal frequency bands (Rosat et al. 2004). Both gravimeters record next to each other (distance about 5 m) on their own pillars. To correct for barometric pressure effects (Warburton and Goodkind 1977, Scherneck 1985, Zürn and Widmer 1995), air pressure is recorded in parallel next to each gravimeter.

The superconducting gravimeter CD-034 is based on a dual-sphere-sensor system. Both spheres are located on top of each other in constant magnetic fields, generated by two superconducting coils each. The feedback system is realised by a non-superconducting inductor. Gravity changes are recorded with a 1 sec sampling interval. For the comparative analyses only the data set of the lower sensor was used.

The L&R gravimeter ET18 consists of a damped spring-mass system with electrostatical feedback installed by Larson (1968). All 1 sec samples are recorded and numerically filtered to 10 sec samples.

For the analyses, the time series of the two gravimeters and barometric pressure sensors include 374 days (July 11, 2007 until July 17, 2008; Fig. 1). The following steps were part of the data preprocessing: numerical filtering to 1 min samples and calibration of the time series with calibration factors of -0.6065 (nm/s²)/mV for the SG and 0.8079 (nm/s²)/mV for the ET18. After that, theoretical tides were subtracted using tidal parameters derived from tidal analyses of 100 day records of the ET18 and the SG (August 4, 2007 until November 12, 2007). The theoretical tides include ter-diurnal, semi-diurnal, diurnal, fortnightly and monthly tidal wave groups. For the tidal analyses and the calculation of the theoretical tides, the program package ETERNA34 was used (Wenzel 1996). Furthermore, barometric pressure was corrected based on the approximated air pressure regression parameters, resulting from the tidal analyses. Regression factors β are (-3.40 ± 0.02) (nm/s²)/hPa for the SG and (-3.40 ± 0.09) (nm/s²)/hPa for the ET18 gravimeters. In short the data processing contains of:

$$\text{residuals} = \text{observations} - \text{theoretical tides} + \beta \bullet \text{air pressure}$$

Processing of the residuals was carried out with the program PreAnalyse (Gebauer et al. 2007). Working steps contained the elimination of spikes and strong earthquakes, correction of offsets and linear interpolation of gaps until 8 hours (in the residual curve). The analyses of the edited time series were accomplished in three different frequency bands: the low frequency band (less than $1.5 \bullet 10^{-3}$ cph), the high frequency band (higher than 0.125 cph) and the Earth tidal frequency intervals in between.

In the three frequency bands tidal analyses, calculation of spectra and regressions were accomplished. One working step was the calculation of a transfer function from the ET18 to the SG. For this, the spectrum of the SG was divided by the spectrum of the ET18 over the whole frequency range from 0 cph until the Nyquist Frequency of 0.5 cph (Fig. 2 and 3). The transfer function has an average of nearly one in the Earth tide frequency bands and the high frequency band, and an average less than one at low frequencies. These results point to the larger drift of the ET18 and they confirm the published results from the other authors (Richter et al. 1995 and Zürn et al. 1991).

3. Comparative analyses in the low frequency band (long-term drifts)

To quantify the long-term drift of both gravimeters the residuals of the 374 days data sets (Fig. 4) were analysed. These residuals contain waves with periods longer than 28 days (equivalent to frequency $< 1.5 \bullet 10^{-3}$ cph = 0.0144 cpd). The residual curve of the ET18 varies in a gravity range of 1447 nm/s², whereas the curve of the SG varies in an interval of 100 nm/s², only.

Linear regression lines were fitted on the residual curves of both gravimeters. The equations for the regression lines are (comp. Fig. 4):

$$\text{ET18:} \quad g = 0.13295 \text{ (nm/s}^2\text{)/h} \bullet t + 2725.663 \text{ nm/s}^2$$
$$\text{SG:} \quad g = -0.00015 \text{ (nm/s}^2\text{)/h} \bullet t + 3063.593 \text{ nm/s}^2$$

with g: gravity value and t: time span in hours. The comparison of the slopes of both regression lines shows the long-term stability of the SG gravimeter (slope nearly zero) and the long-term drift of the L&R gravimeter.

After subtraction of the linear drift, the variation of the residuals of the ET18 is in the range of 759 nm/s², and the variation interval of the SG is still 100 nm/s².

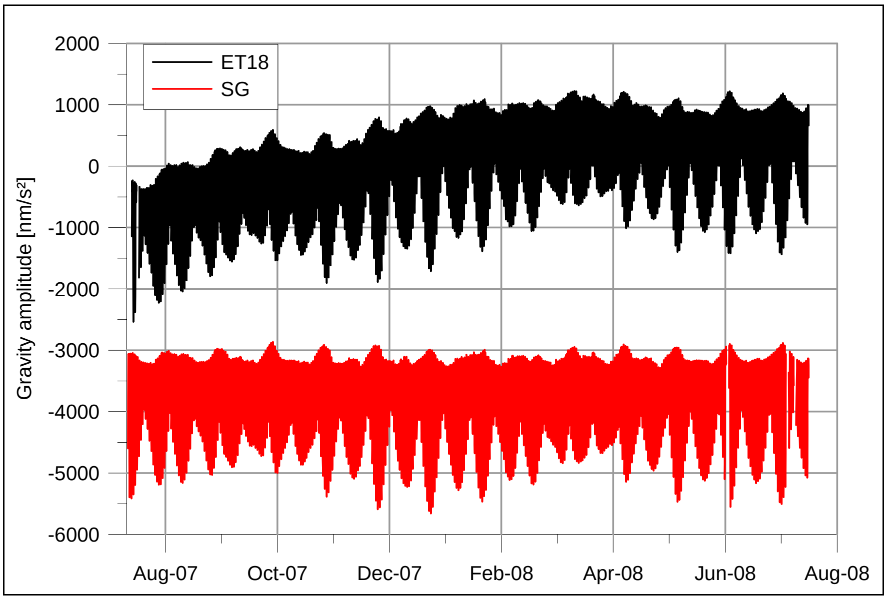

Fig. 1: Time series of the ET18 gravimeter and the SG gravimeter over 374 days (July 11, 2007 until July 17, 2008).

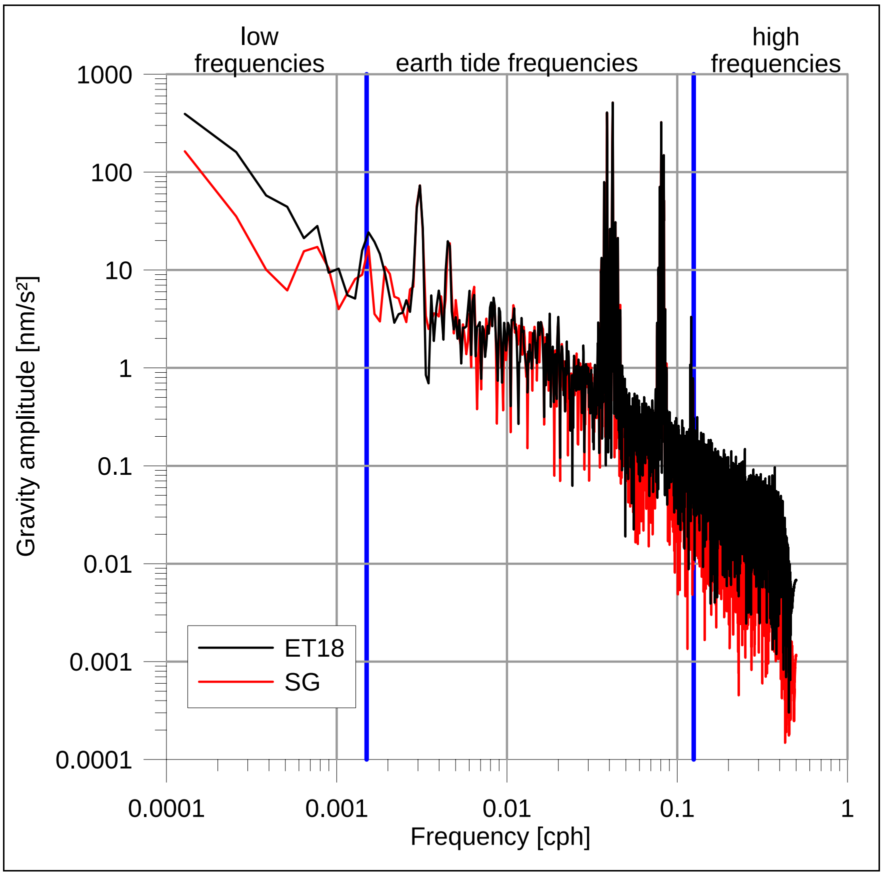

Fig. 2: Spectra of the ET18 gravimeter and the SG gravimeter over the whole frequency range.

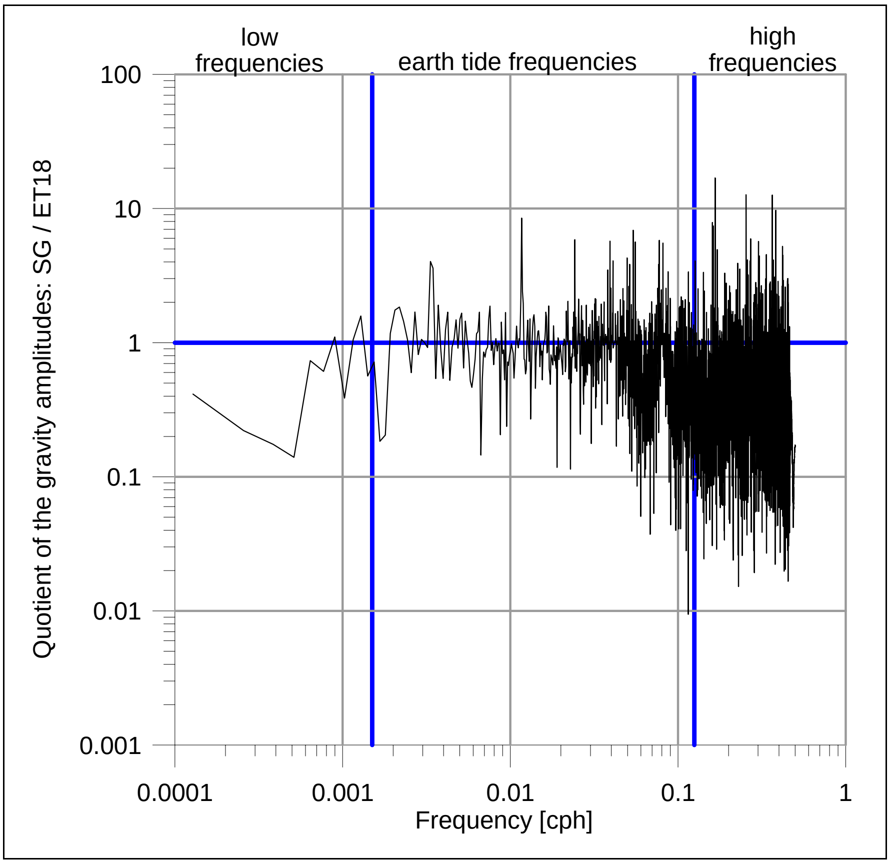

Fig. 3: Transfer function between the ET18 gravimeter and the SG gravimeter over the whole frequency range.

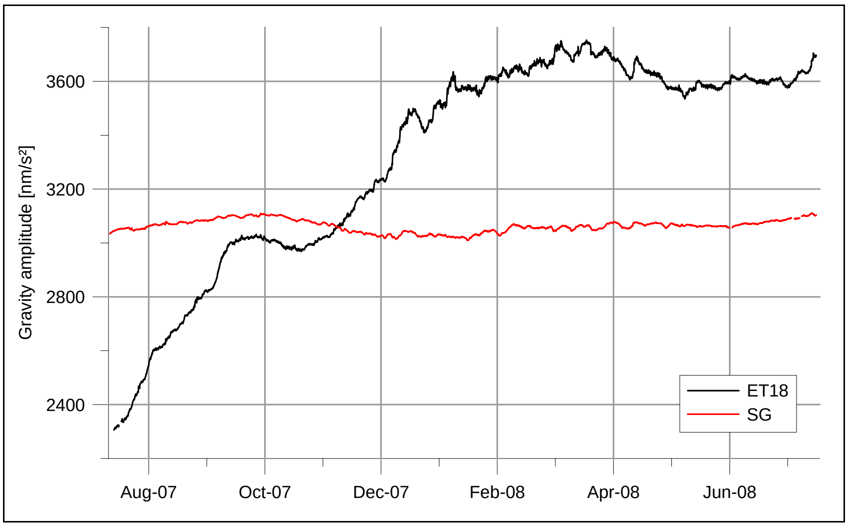

Fig. 4: Long-term drift of the ET18 gravimeter and the SG gravimeter. Both records contain waves with periods longer than 28 days.

4. Analysis of the Earth tide frequency ranges

The Earth tide bands include waves with periods between 8 hours and 28 days. With the Earth tide data processing package ETERNA34, the preprocessing and analysis of Earth tide observations, the prediction of Earth tide signals and the computation of ocean tide loading are possible. The adjustment of the tidal parameters is based on the least squares method. Results are the amplitude factors δ and phase differences α. The amplitude factors δ for the tidal wave groups are calculated by the equation:

$$\delta = h / H$$

with h: amplitude of the tidal wave group of the gravity record, which is analysed; H: amplitude of the tidal wave group from the tidal potential catalogue according to Hartmann and Wenzel (1995; HW95). The phase differences α are results of the equation:

$$\alpha = \varphi - \Phi$$

with φ: phase of the tidal wave group of the gravity record, which is analysed; Φ: phase of the tidal wave group from the tidal potential catalogue HW95.

After the correction of both records as mentioned above, theoretical tides and barometric pressure were added to the computed residuals of the gravity records. In short the data processing covers:

$$\text{edited observations} = \text{edited residuals} + \text{theoretical tides} - \beta \bullet \text{air pressure}$$

with β: estimated air pressure regression parameter, resulting from the tidal analyses with ETERNA34 of the 100 day data sets from the ET18 and SG. Then, the edited observations were filtered to one hour samples.

The tidal analyses of the two time series were carried out in two steps: first, for the ter-diurnal, semi-diurnal and diurnal tidal wave groups and second, for the fortnightly and monthly tidal wave groups. The reason for the two step calculation is to get the best fitted results for the ter-diurnal, semi-diurnal and diurnal tidal parameters. In the first analysis step the gravity and barometric pressure data were filtered by a low pass filter with 167 supporting points and a cut-off frequency of 0.0333 cph (equivalent to a period of 30 hours). In the second step, the edited observations were used without any filter.

The results of the tidal analyses are the tidal parameters (which still contain the ocean loading effect, Tab. 2 and 3) and the averages of noise levels at the different frequency bands (Tab. 4). Furthermore, the signal-to-noise ratios for the analysed tidal wave groups were calculated (Tab. 2 and 3). These signal-to-noise ratios of the ter-diurnal, semi-diurnal and diurnal tidal wave groups from the ET18 are a factor of 6 lower than these of the SG. Ratios of the fortnightly and monthly tidal wave groups from the ET18 are a factor of 3 lower than of the SG. The big differences in the tidal parameters for the fortnightly and monthly tidal wave groups are caused by the long-term drift in the ET18 record and the long-term stability of the SG data set.

Another result of the analyses is given by the comparison of the spectra of the residuals. The residuals are the difference between the observed data and the fitted theoretical tides by the least squares method. In the spectra of the residuals from the ET18 and SG analyses (Fig. 5), no significant information at the known tidal frequencies is found. Thus, the calculated tidal parameters are a good fit to the recorded Earth tides. The residual amplitudes in the spectra from the ET18 are a factor 10 higher than of the SG.

Tab. 2: Tidal parameters and the signal-to-noise ratios for the ET18 gravimeter record.

wave group	δ-factor	phase delay [°]	s/n ratio
MM	1.24644 0.26448	6.3987 12.0211	11
MF	1.13596 0.04633	3.0390 2.3782	19
O1	1.14907 0.00058	0.1236 0.0289	1389
K1	1.13701 0.00045	0.1438 0.0227	1932
M2	1.18582 0.00034	1.5707 0.0165	2899
S2	1.18245 0.00068	0.1716 0.0333	1345
M3	1.07147 0.01755	-0.3132 0.9384	48

Tab. 3: Tidal parameters and the signal-to-noise ratios for the SG record.

wave group	δ-factor	phase delay [°]	s/n ratio
MM	1.14555 0.09422	5.4032 4.6392	29
MF	1.12844 0.01635	-0.5810 0.8508	54
O1	1.14880 0.00010	0.0760 0.0047	8480
K1	1.13653 0.00007	0.1851 0.0038	11794
M2	1.18551 0.00006	1.4858 0.0028	17342
S2	1.18428 0.00011	0.2485 0.0056	8059
M3	1.07135 0.00249	0.0071 0.1334	339

Tab. 4: Averages of noise levels at the different frequency bands for the analysed ET18 and SG data sets.

	$4.17 \cdot 10^{-3}$ cph	0.0417 cph	0.0833 cph	0.125 cph
ET18 [nm/s²]	2.992	0.252	0.124	0.085
SG [nm/s²]	1.060	0.041	0.021	0.012

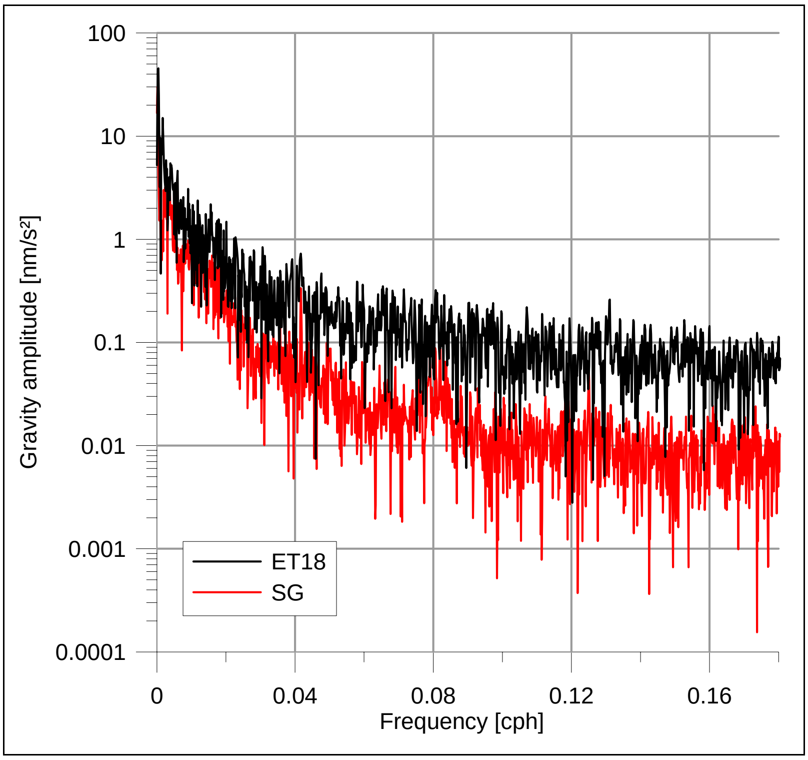

Fig. 5: Frequency spectra of the residuals from tidal analyses for the ET18 gravimeter and SG gravimeter.

5. Comparative analyses in the high frequency band (free modes of the Earth)

After strong earthquakes the Earth oscillates with a sum of discrete spheroidal and toroidal modes. Spheroidal modes are affected by the gravitational field of the Earth and can be measured using gravimeters. For the determination of the free modes three strong earthquakes were cut out of the gravity records of the ET18 and the SG (source: earthquake catalogue USGS NEIC):

1. August 15, 2007 near the coast of central Peru with a magnitude of 8.0
2. September 13, 2007 southern Sumatra with magnitudes of 8.5
3. May 12, 2008 eastern Sichuan, China with a magnitude of 7.9

Each of the three data sets has a length of 49 hours. Figure 6 shows the residuals of the time series (detided and depressured) of the ET18 and SG for the earthquake in eastern Sichuan, China. For all records discrete Fourier spectra between 0.25 mHz and 4 mHz (periods between 67 min and 4 min) were calculated. Furthermore, the spectra were stacked for each gravimeter to increase the signal-to-noise ratios. Results are 28 spheroidal free modes (frequencies of the modes after Masters and Widmer 1995) in the stacked spectra (Fig. 7). As can be seen, the noise level of the ET18 is slightly higher than the one of the SG until a frequency of 1.5 mHz. Moreover, the amplitude values of the frequency peaks in the ET18 spectrum are a bit lower than the peak values of the SG spectrum. From these two facts follows, that the signal-to-noise ratios of the ET18 are smaller than those of the SG. Nevertheless, the information content in both spectra is the same.

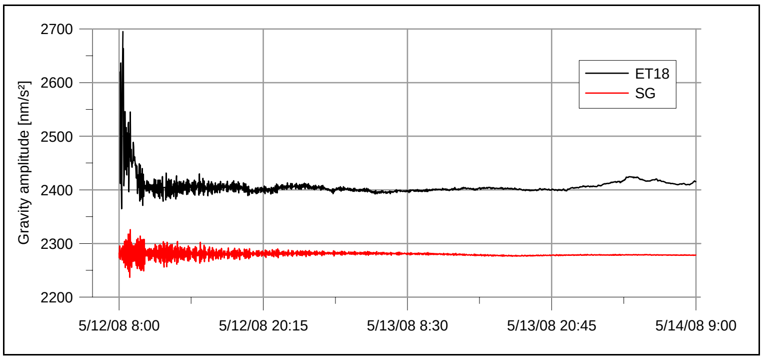

Fig. 6: Reduced time series from the China earthquake (May 12, 2007).

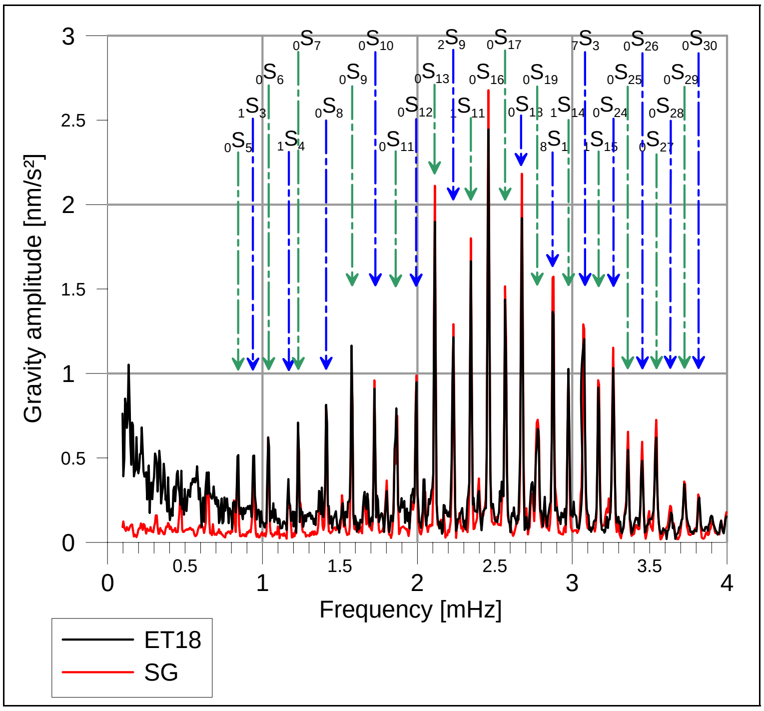

Fig. 7: Stacked spectra of three earthquakes of the ET18 and the SG gravimeter with 28 spheroidal free modes of the Earth.

6. Conclusions

With one year parallel records of the L&R gravimeter ET18 and the superconducting gravimeter CD-034 at the Geodynamic Observatory Moxa it was possible to carry out a comparison between these different gravity measuring systems. The analyses of the time series were conducted in three frequency ranges: the low frequency band (< $1.5 \cdot 10^{-3}$ cph), the high frequency band (> 0.125 cph) and the Earth tide frequency intervals in between.

The results show in the low frequency band a long-term drift in the ET18 record and a long-term stability in the SG time series, in the high frequency range (free modes of the Earth) nearly identical information content in the data sets of both gravimeters, although higher noise level in the ET18 record up to a frequency of 1.5mHz and lower peak values in the spectrum compared to the SG data. Furthermore, in the Earth tide frequency intervals the information content in both time series for the ter-diurnal, semi-diurnal, diurnal and fortnightly tidal wave groups is also identical, although a higher noise level by a factor of 6 in the ET18 record compared to the SG. For the monthly tidal wave groups, the tidal parameters from the ET18 data set are higher than these of the SG. The reason may be the energy provided by the long-term drift in the ET18 time series.

These investigations show that one of the best spring gravimeters, the L&R Earth tide gravimeter ET18 is comparable to the superconducting gravimeter for periods of 14 days and shorter. The advantage of the L&R gravimeter is the mobility. Therewith, the newly calibrated and tested ET18 is ready to be used for recording of gravity changes at different stations.

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