Investigations to improve the Signal-to-Noise-Ratio in Data from Superconducting Gravimeters in the Short-Period Spectral Range

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Abstract:
The noise level in processed time series from superconducting gravimeters (SG) is mainly caused by not fully reduced atmospheric and hydrological influences. Therefore, we investigated whether an improvement compared to usual reduction methods can be achieved by using: i) highly resolved (both temporally and spatially) 2D surface data of air pressure and temperature in an approach according to Merriam (1992); ii) 3D atmospheric model data (from the WRF) with explicit consideration of the humidity of the air and its distribution.
However, our studies showed that both the 2D- as well as the 3D-atmospheric correction do not give an improvement in the noise level of SG gravity residuals at periods between 2 h and 48 h. This means that the available meteorological 2D- and 3D-datasets are not yet sufficient for an improved reduction of atmospheric influences in the short period spectral range and that the standard air pressure reduction method (using a regression coefficient, i.e. an admittance) is still the most effective reduction method in the short-period spectral range.

1. Goals of our research:

Data from superconducting gravimeters (SG) are nowadays an essential tool to explore global geodynamic phenomena, such as mass displacements or deformations of the crust. SG show a high long-time stability and generally a better signal-to-noise ratio (SNR) than spring instruments (Rosat and Hinderer 2011).

In the search for smallest geodynamic signals it is a prerequisite to eliminate further disturbances from SG time series which manifest themselves as different kinds of noise. During the last years, clear improvements were obtained in the long-period spectral range due to air pressure reduction using 3D atmospheric model output (e.g., Abe et al. 2010, Klügel and

Wziontek 2009). In the short-period spectral range, such a progress in improvements of SNR has not yet occurred. Especially for periods between 2 h and 2 d, an increase of the SNR would be very desirable, as a number of important geodynamic signals is theoretically expected to exist, as for example:

- Translational oscillations of the solid inner core of the Earth, the so-called Slichter mode with a period larger than 5 h (split into a triplett due to Earth rotation and ellipticity).
- Rotational oscillations in the outer, fluid core with anticipated periods of about 24 h and 17 h.

Furthermore, an increase in the SNR in the period range up to 48 h would allow an improved determination of station-specific Earth tide parameters and hence a better data basis for evaluating ocean tide models and loading Love numbers. Despite of existing reduction methods, atmospheric effects still are the greatest disturbing influence in this period range.

The goal of this study was to clarify whether an improvement of reduction of atmospheric influences in observed terrestrial gravity time series can be obtained, if we use:

- Observed highly resolved (spatially and temporally) surface data (pressure p, temperature T), and:

- Modeled 3D-atmospheric-data including the humidity of the air (i.e., without the use of a virtual temperature).

2. Data used and methods of reduction

The two types of data sets (2D and 3D) as used in the present study mainly cover the area of Germany, as there are three existing SG stations and a meteorological observation network is available for Germany. But we focused on the stations Moxa (MO) and Bad Homburg (BH) only. The third mentioned station Wettzell (WE) which is close to the border of the Czech Republic was not involved because of two reasons:

i) The air pressure and temperature data from the Czech Meteorological Service were too expensive and were not available in the favored spatial resolution;

ii) Wettzell displays significant, very locally caused hydrological effects, whose adequate reduction is not yet possible (e.g., Klügel and Wziontek 2009, Creutzfeldt et al. 2010).

We chose for our study the time interval from January 1 to June 30 in 2006, because in this time interval both the highly resolved surface data and modeled 3D data were available.

As a preparation, the gravity time series of both stations (MO, BH) were filtered to 10 min (for 2D) or 1 h (for 3D) time steps. Small data gaps of up to 2 h were interpolated linearly. Both time series were reduced concerning Earth tides and ocean loading. Tidal as well as non-tidal ocean loading was considered, the latter according to the ocean model OMCT (Dobslaw and Thomas 2007). The gravity time series of the station Moxa was additionally reduced for local hydrological effects (Naujoks et al., 2010).

Then we computed the atmospheric corrections according to the following details:

3. Use of highly resolved surface data (2D), Merriam method

Observed, highly resolved surface data (surface pressure and temperature) from 96 meteorological stations in Germany were available. We purchased these data from DWD (Deutscher Wetterdienst). These data span from January 1, 2004 to December 31, 2007, with a time step of 10 min.

As a preliminary step, these DWD data were checked (removal of outliers; interpolation of small gaps). Then they were interpolated to a regular latitude/longitude grid using the MINC algorithm (Minimum Curvature, i.e., splines).

Using these grids, atmospheric corrections for the stations MO and BH were computed. This was done according to the method proposed by Merriam (Merriam 1992). In the calculation of the Newtonian attraction part a vertical pressure and temperature distribution is used which is based on a model atmosphere together with the pressure and temperature values at the Earth's surface. For the deformation part, Green's functions are used (Farrell 1972). These reductions were applied to the gravity residuals and compared to the standard reduction (using a regression coefficient (admittance) computed between local air pressure and gravity, cf. Torge 1989, Melchior 1983).
The deformation part of the Merriam correction was calculated using sea-level pressure (SLP), which was obtained from surface pressure and temperature via the barometric height formula. We included the Merriam temperature correction part; this cannot be neglected.
After the Merriam correction (and also after the 3D correction in Chapter 4), a regression was applied between the gravity residuals and the local station air pressure, and the result was subtracted from the gravity residuals. However, this procedure has little effect on the resulting final gravity residuals and their RMS. (The coefficient of correlation between the 2D corrected residuals and the local air pressure is near +0.20 … +0.25, depending on the station [Moxa or Bad Homburg] and on the time interval considered.)

4. Usage of 3D data

The 3D atmospheric fields used were obtained from the Institute for Meteorology and Climate Research (IMK-IFU) in Garmisch-Partenkirchen which is a branch of the KIT (Karlsruhe Institute of Technology). They were computed in a high resolution simulation with the WRF-ARW model (The Weather Research and Forecast Model, Skamarock et al. 2008). These data are given on a big 'square' over all of Europe with a horizontal resolution of 10x10 km^2. In the vertical, they consist of 41 layers up to about 28 km altitude. The data were provided with a temporal resolution of 1 h and they cover the time interval from January 1 to June 30, 2006. Due to the computational demand, only a single configuration of the atmospheric model could be exercised within the presented study. The setup consisted of version 3.1.1 of the WRF-ARW model and physics selected as follows: WSM 5-class microphysics, RRTM long-wave and Goddard short-wave radiation, YSU PBL scheme, NOAH land surface model, and Kain-Fritsch convective parametrization.
The computation of the 3D atmospheric correction was done using a given C++ program that had been created at GFZ Potsdam as part of a Diploma thesis (Stöber 2005). This software tool was adapted to the present 3D data. It calculates both the attraction and the deformation part.

For the attraction part, we used spherical volume elements for which a closed expression exists involving square roots and logarithms (Neumeyer et al. 2004, 2006).

It is first necessary to transform the 3D data (1.1 TByte) from the 'Lambert conformal conic projection' to a regular latitude/longitude grid. We chose grid cells of 0.10°x0.10°.

The following data variables were used in the computation of the 3D atmospheric correction:

- density of air (3D),
- geopotential (3D),
- surface pressure (2D),
- topography (2D) [which is smoothed to 10 km],
- land-ocean-mask (2D)

For the 3D calculations, the geopotential at the Earth's surface (lowest level) was constructed as: i) equal to zero over the oceans;
ii) from the height of the topography over land.

Furthermore, the deformation part was computed using the surface pressure instead of the sea-level pressure, because sea-level pressure (or surface temperature) data were not available for a temporal resolution of 1 h.

As the 3D data go up to an altitude of about 28 km only, we appended an extrapolated Standard Atmosphere (for mean latitudes) above 28 km up to 60 km altitude.

5. Description of the results and discussion

Both atmospheric reduction methods as discussed above (2D and 3D) were applied to the gravity residuals for MO and BH, and the results were compared among each other and with the standard reduction method.

Fig. 1 shows the 2D-correction (Merriam method, upper plot) for the station Moxa compared to the standard pressure correction and compared to the 3D-method (lower plot). From this Figure, we can deduce:

- The calculated 2D- and 3D-corrections have almost the same temporal behavior as the standard correction method.
- The 2D-reduction (upper plot) has only very small deviations from the standard reduction method. However, there are relatively large deviations between the 3D- and 2D-method (lower plot, e.g., at ~60.000 min and ~220.000 min). For some time intervals, the 3D-correction looks 'like a smoothed version' of the 2D-correction.

The differences between the three methods are more clearly visible after the application of the atmospheric correction to the gravity residuals. This is shown in **Fig. 2** for both SG-stations. In this Figure, the gravity residuals of Moxa and Bad Homburg are compared after applying an atmospheric correction according to the three methods (standard pressure correction, 2D method after Merriam and 3D correction). From the plots for both stations, we can infer:

- The temporal behavior of the 2D atmospheric correction (Merriam method, green curve) is in a good agreement with the standard air pressure correction (red curve). However, it's obvious that the 2D method gives a significantly higher noise (c.f. the red and green curves in Fig. 2 for Moxa and Bad Homburg). This finding is also reflected by the RMS values of the residuals (for example: Moxa: 5.5 nm/s^2 for the standard air pressure correction versus 6.05 nm/s^2 for the 2D-correction).
- The remaining residuals after the application of the 3D atmospheric correction show a significantly different behavior compared to the 2D-correction and the standard air pressure correction. Please note particularly the positive and negative 'spikes' near ~100.000 min und ~170.000 min for both stations.
- From a comparison with other meteorological information, we found out that the strong 'spike' near ~100.000 min took place when a front passed and air pressure increased suddenly. The 'spike' caused by the application of the 3D atmospheric correction is an indication that short-time pressure rises are not yet correctly modeled in the underlying WRF model 3D data.

The **Figures 3** and **4** show the PSD (Power Spectral Density) of the gravity residuals from Fig. 2. Here, we only plotted the spectra from the 3D method compared to the standard method, both for Moxa (Fig. 3) and Bad Homburg (Fig. 4). Two plots are shown for each station with different frequency axes: linear (bottom) and logarithmic (top). The corresponding spectra for the 2D atmospheric correction are not shown here, because they are not significantly different from the standard method.

From **Fig. 3** and **4** we conclude:

- It's clearly visible that the spectra for the 3D atmospheric correction have a higher spectral power than those for the standard reduction method. This means that the application of the 3D atmospheric correction caused a rising of the noise level in the final gravity residuals.
- Both spectra (using 3D- and standard air pressure correction) contain the same peaks near higher harmonics of the diurnal variation (frequencies: 1/d, 2/d, 3/d).

Comparing the reduction results, we come to the following conclusions:

1. The **Merriam method** by using **2D data** from DWD produced a small increase in the noise of the gravity residuals compared to the standard method. The reasons for this finding could be:

   - There are parts in the atmosphere which do not correlate with the meteorological variations at the Earth's surface. These parts have a stronger influence than assumed,

   - Effects from the near surrounding area (some 10 km around the gravimeter) have a stronger influence than assumed; that means a very fine observation mesh would be necessary for significant improvements in the future.

2. The temporal behavior of the 3D correction differs more strongly from the standard air pressure correction than the 2D Merriam method. In particular the applied 3D correction

produces some incorrect ‘spikes’. This indicates that the present quality of the 3D data is not yet sufficient to give an improvement in the atmospheric reduction of gravity time series compared to the standard air pressure method. Nevertheless, one should have in mind that only an individual realization of a high resolution atmospheric model was applied. Different configurations of WRF-ARW are known to yield different results, in particular with respect to the moisture budgets (Fersch et al. 2009). Additional comparisons with alternative setups should be tested in order to investigate possible variations. For instance, in contrast to other models, the selected configuration of the WRF-ARW model explicitly considered the humidity of air, but this is obviously not sufficient for an improvement in the atmospheric reduction.

Our conclusion is that the standard air pressure reduction (admittance coefficient) is presently still the most effective reduction method in the short-period spectral range, although this method produces some small errors near the higher diurnal harmonics, because of the global character of pressure variations near these periods.

Investigations by Gebauer et al. (not yet published) within the DFG-project KR1906/7-1 have shown that the deformations of the crust at a typical SG location are caused to 98% by the structure of the loading field at every observation time. Maximally 2% of the effects are caused by topography and crustal heterogeneity. This result (as well as the insights concerning the strength of the attraction effect in the zone of some 10 km around the gravimeter) clearly imply that the strategy of higher temporally and spatially resolved meteorological data must be pursued further. It seems that the available meteorological data sets are not yet sufficient in the short period spectral range. One option to overcome this drawback exemplarily could be the installation of a high resolution meteorological observation net around a dedicated SG station. There are efforts in this direction, but from our knowledge a high resolution 2D observation net has not yet been established. The registration of the vertical atmospheric variations above an SG site is an open question. One option could be the usage of atmospheric variation measurements derived from GPS observations at the SG location.

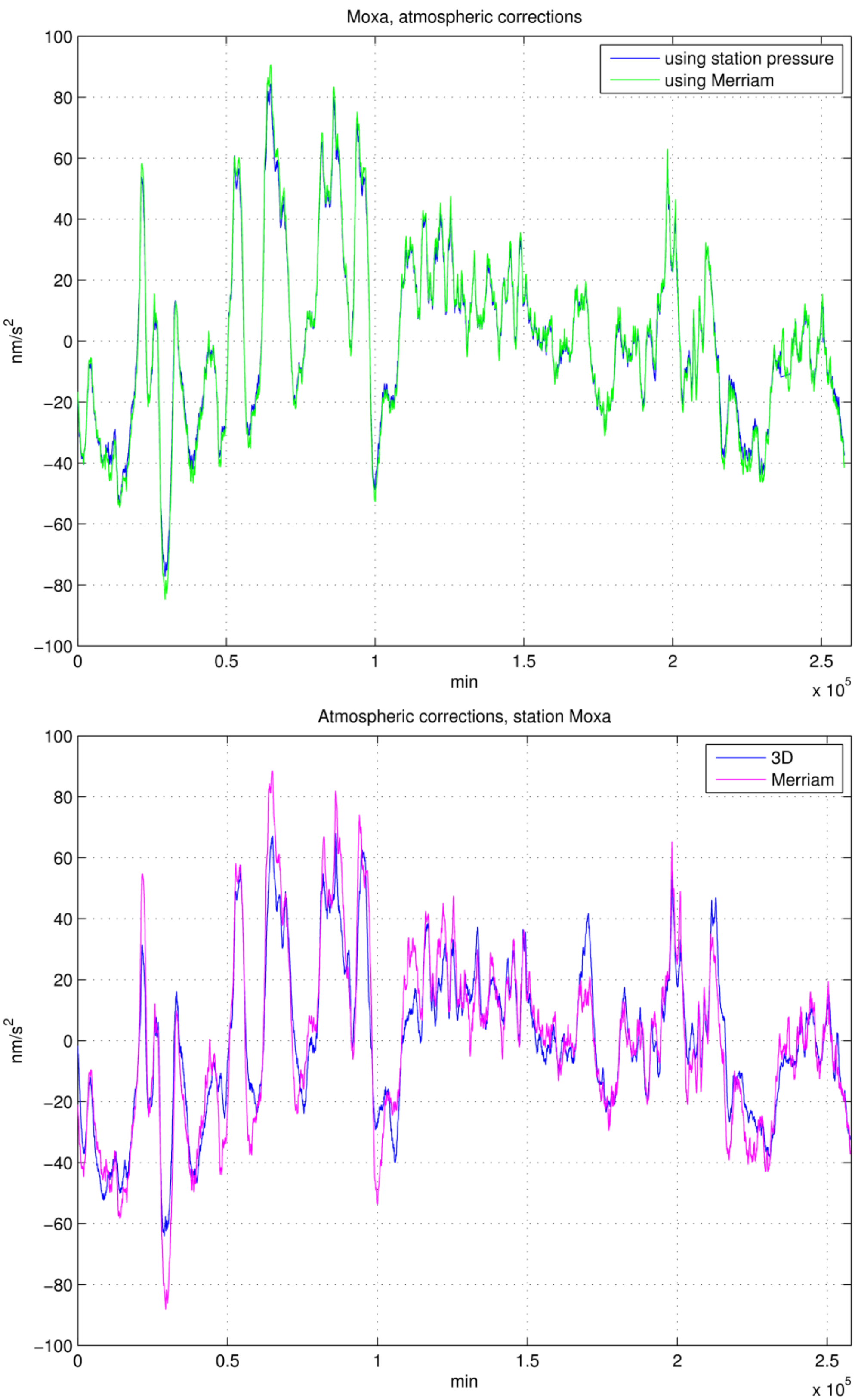
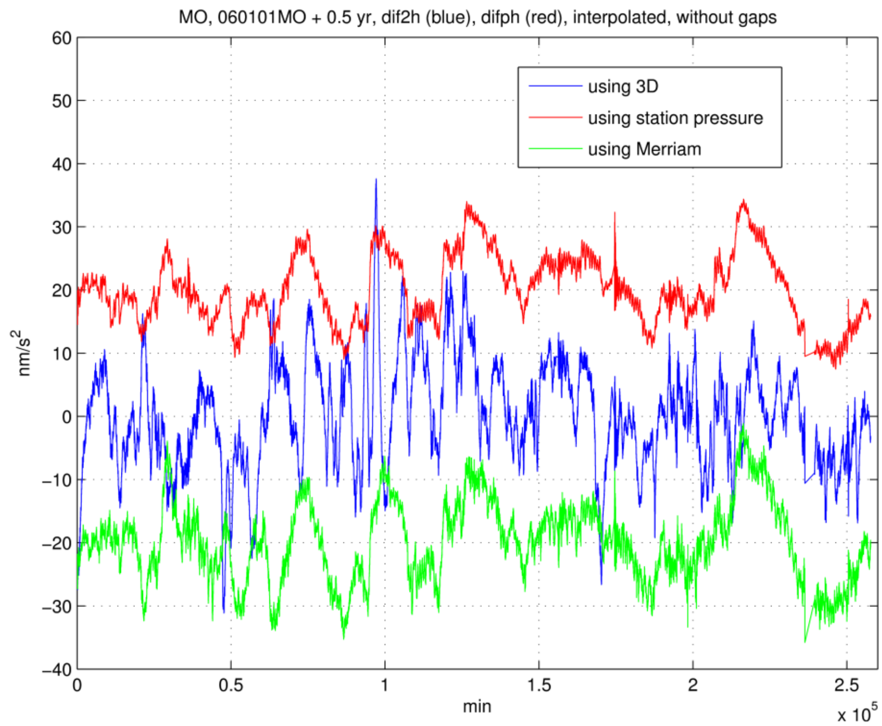


Fig. 1: Atmospheric corrections at the SG station Moxa from the 2D-data (method of Merriam) compared to the standard air pressure correction (upper plot) and compared to the 3D-method (lower plot). The time axis is given in [min] since January 1, 2006.



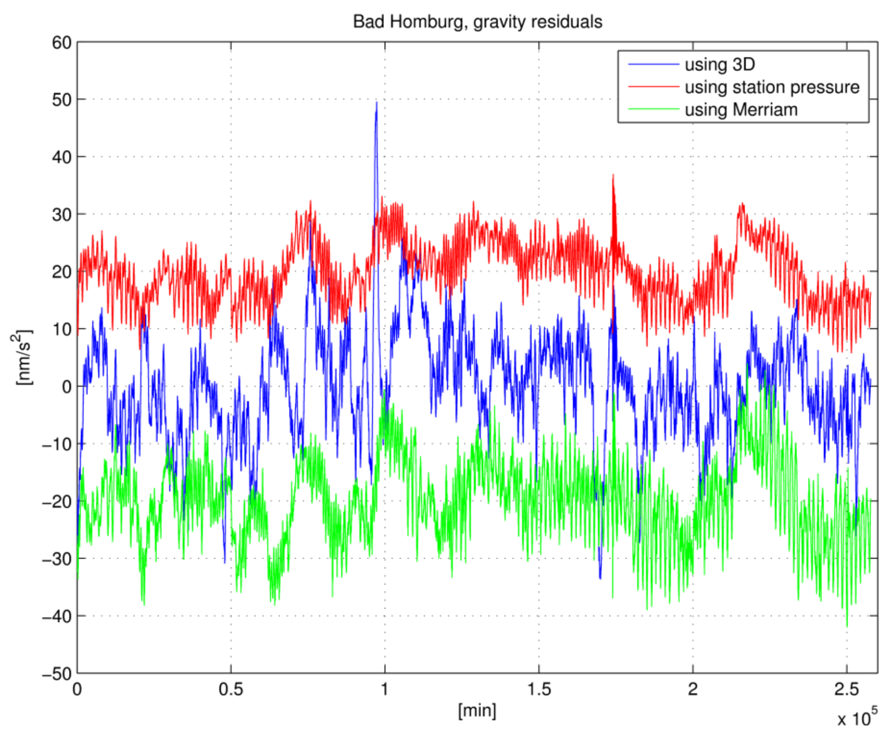


Fig. 2: Gravity residuals for the stations Moxa (upper plot) and Bad Homburg (lower plot) when using the standard air pressure correction (red), the 3D-correction (blue) and the Merriam-correction (green) for the time interval January 1, 2006 to June 30, 2006. Please note, that constant offsets have been added to the red and green curves compared to the blue curves.

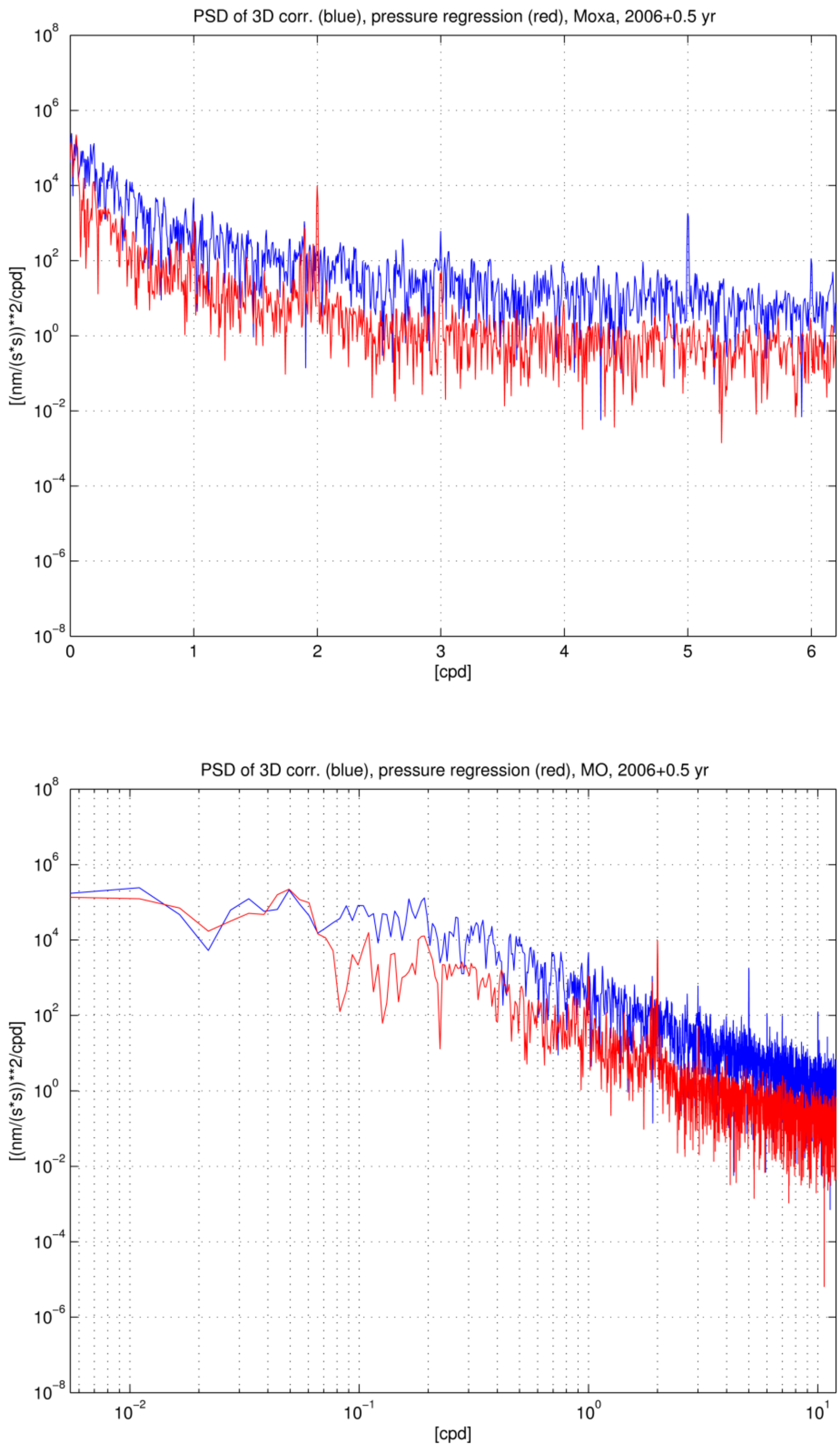


Fig. 3: Power Spectral Density (PSD) of the gravity residuals at the SG station Moxa for the 3D-method (blue) and the standard air pressure correction method (red), with linear (upper plot) and logarithmic frequency axis (lower plot).

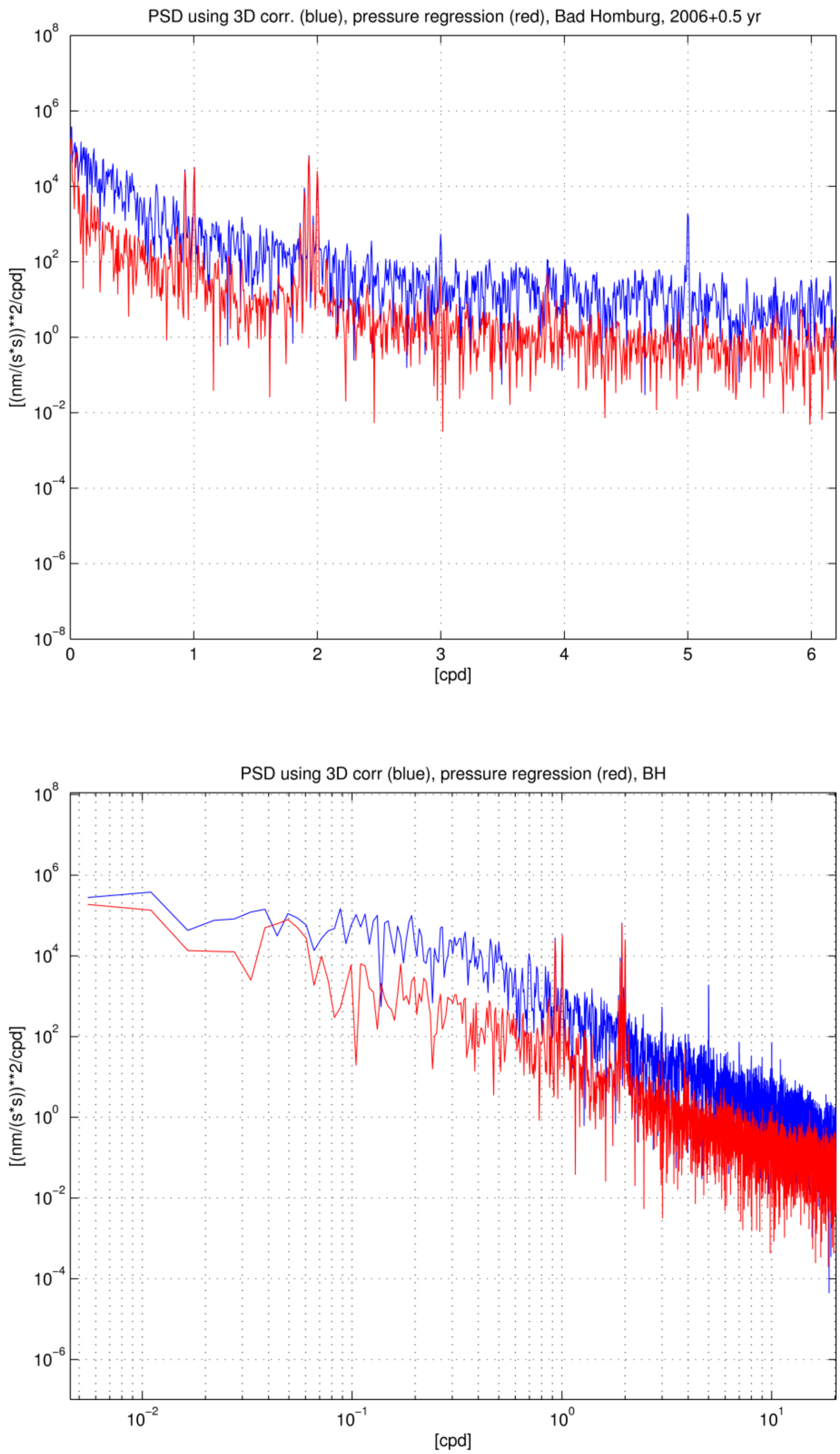


Fig. 4: Power Spectral Density (PSD) of the gravity residuals at the SG station Bad Homburg for the 3D-method (blue) and the standard air pressure correction method (red), with linear (upper plot) and logarithmic frequency axis (lower plot).

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