Preparation of Data from Superconducting Gravimeters for Investigations in the Frequency Range around 100 µHz.

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Abstract: Signals of unknown origin can be detected in the SG gravity data only after the interfering tidal oscillations are removed. The inverse FFT filtering method, unlike the usual high-pass filters, can handle the huge differences in amplitudes without additional noise. The procedure is described in detail.

Introduction: Superconducting gravimeters are remarkably sensitive instruments for the vertical component of gravity and are ideally suited for long-term measurements in the frequency range between 2 µHz and about 10 mHz, which is of interest not only to geophysicists. From an astronomical perspective, the Earth is the largest possible test mass for searching for oscillations that could be caused by distant objects or in the Earth's interior. The strong influence of nearby celestial bodies, such as the Sun or Moon, is well known and interferes with the search for weak signals. Although the frequencies of these periodic changes are tabulated[1], it is not easy to remove them from the measured signal mixture without disturbing the weak signals that may be present. A method for direct compensation of unwanted frequency ranges is described in detail below.

The noise level of the gravimeters operated so far is significantly higher than expected from the technical design of the instruments, because the gravimeters are – from an acoustic point of view – unfavorably mounted: They are firmly connected to the ground and therefore receive the structure-borne sound of even distant earthquakes. This immediate transmission of vibrations to the gravimeter housing could be significantly reduced by elastic suspension, but unfortunately has not yet been tested.

Origin of the basic data: Stations distributed all over the world register the data of the gravimeters, which are converted to a uniform format in the IGETS Central Bureau and stored in a central location in text form (ASCII coding)[2]. To simplify the construction of long, gapless data sequences, all data gaps in the currently used data format are replaced by synthetic tidal data. In contrast, the older data formats from the early years of superconducting gravimeters contain many data gaps, the elimination of which requires additional effort.

Since gravimeters measure the vertical component of the gravitational force, they also respond to the variable air mass above the measurement location. This changes with the weather (air pressure and humidity). While altitude and air pressure can be easily measured at the gravimeter's location, determining the mean humidity is so complex that it is usually not done. The result is an increased noise background.

To account for all readily available influences, the gravity data sought are calculated as the weighted sum of the data series from the gravimeter (column 9 of the IGETS files) and barometer (column 7). The optimal mixing ratio depends on the height of the gravimeter above sea level and must be determined empirically. A possible target is to minimize the noise in a certain frequency range that is not too narrow and does not contain strong, detectable resonances. For the gravimeter SU (Sutherland/Africa at 2800 m altitude) applies $y_{97}=y_9-1.3\times y_7$. For the lower gravimeters in Europe and Australia, use the formula $y_{97}=y_9-1.6\times y_7$.

1 Hartmann, T. and H.-G. Wenzel (1994): Catalogue of the earth tide generating potential due to the planets. Geophysical Research Letters, vol.21, pp. 1991-1993, 1994.

2 GFZ Potsdam, IGETS Datenbank

Removal of tidal signals: The spectrum (Figure 1) shows that extremely strong low-frequency oscillations below 35 µHz dominate the gravity data. They drown out all weak signals in the survey area by a factor of at least 10^5 and must be removed if the search for weak oscillations in the frequency range between 40 µHz and 400 µHz is to be promising. Extensive tests have shown that the usual digital high-pass filters are not very suitable for this purpose because they further increase the already enormous noise level. The reason can be explained simply: The function of digital filters is based on the fact that several copies of the recorded data are time-shifted and attenuated and added to the original data. Solitary noise peaks, which would actually only have an effect as high-frequency noise, thus appear at several time positions. This broadening over a larger time range is equivalent to a previously non-existent low-frequency component that increases the noise level.

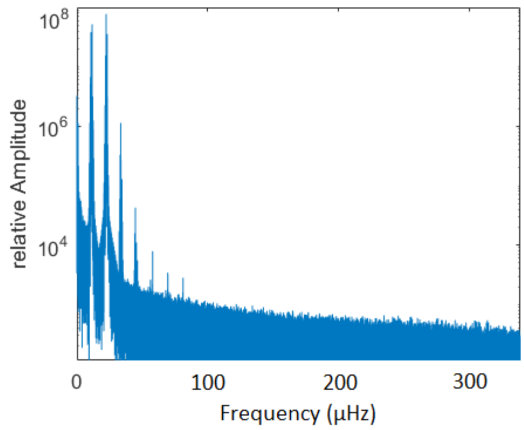

Fig. 1: Spectrum of the unfiltered gravitational data (location = SU)

This disturbing side effect can be avoided by replacing the high-pass filter by a compensation method: One reconstructs only the low-frequency and uninteresting part of the gravitational data by noise-free sinusoidal functions and subtracts this from the original signal mixture. No high demands are made on the reconstruction of the unwanted and very intense spectral lines below 35 µHz by means of a simple Fourier analysis/synthesis. The only decisive factor is that the weak signals and all frequency components in the examination range around 100 µHz remain unchanged so as not to generate additional noise. Solitary noise peaks are often found in the data sets, which can subsequently be removed manually.

The Fourier transform allows to approximate arbitrary time series by a set of noise-free sinusoidal functions – in the present case the reconstruction of the original time series is limited to frequencies smaller than 35 µHz. It is irrelevant whether the frequencies and amplitudes of the unwanted spectral lines are constant in this range or not. It is also not necessary to determine the interfering frequencies exactly with the FFT method. Poor reconstruction of the unwanted frequency range below 35 µHz results in incomplete compensation of the interfering spectral lines. This corresponds to a high-pass filter with low blocking effect for low frequencies and is unproblematic as long as the amplitude of the interfering tidal oscillations are sufficiently damped.

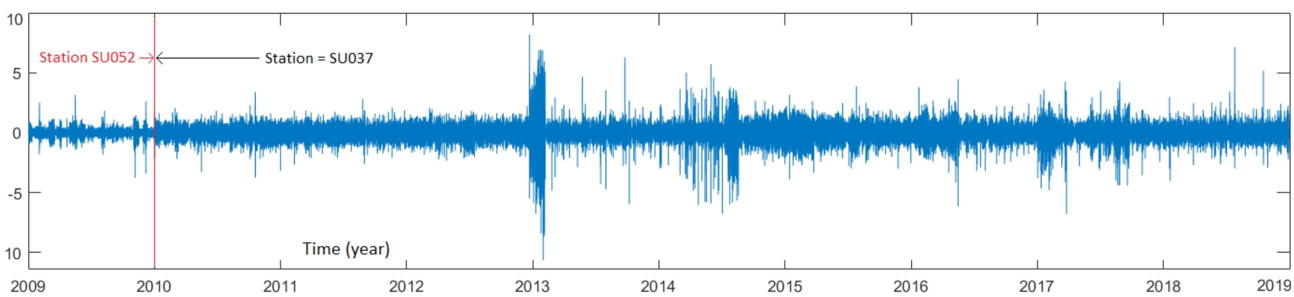

Fig. 2: Gravity data from SU after compensation of all frequencies below 35 µHz.

The example shown in Fig. 2 of a ten-year data series recorded in South Africa (SU) shows serious differences in quality: In 2010, the gravimeter was replaced by a poorer successor model with increased background noise. In early 2013, experiments were conducted in close proximity to the instrument for about a month. Further experiments followed during 2014. Since ground shaking is not a gravitational event, a properly mounted gravimeter should not respond to it.

Program example: The following program lines outline the inverse FFT filtering procedure. Thanks to the preliminary work done by IGETS, the measurement data can be read in and immediately linked without time-consuming corrections and additions.

```
load 'Raw_data_SU371' %Data from IGETS; years = 2009..2018
y9=y(:,9); y7=y(:,7); %isolate the required columns
y97=y9-1.3*y7; plot(y97) %empirical factor 1.3 for h≈2800 m

%For h≈300 m, the empirical factor is 1.6
```

The variable y97 contains the corrected measured values; Now the sampling time of the gravity data (Ts = 60 s) is extended to reduce the data size.

```
y=decimate(y97,5,'fir'); y=decimate(y,4,'fir');
Ts=60*5*4; L=length(y); %Reduction of the data length

%inverse FFT-filter = high pass
NFFT = 2^(nextpow2(L)); %minimum length of the FFT
f=1/Ts/2*linspace(0,1,NFFT/2+1); y7F=fft(y,NFFT);
j=1; while f(j)<34.8e-6; j=j+1; end %choose cutoff frequency
y7F(j+1:NFFT-j)=0; %do not reconstruct high frequencies
y7F=ifft(y7F,NFFT,'symmetric'); %inverse transformation
y=(y-y7F(1:L)); plot(y) %compensate the low frequencies
```

Result: The gravity data obtained in this way in the frequency range 35 µHz to about 400 µHz (see Fig. 2) should be checked manually to see whether they contain solitary spurious peaks and/or jumps that were probably not caused by changes in gravity. Their removal will reduce the noise level of the data series.

The frequency grid of 11.57 µHz in the spectrum (Fig. 3) is due to atmospheric oscillations. Depending on the quality of data preparation, these can be identified up to the maximum frequency 190 µHz. The group of spectral lines at 300 µHz corresponds to the lowest natural resonance 0S2 of the earth excited by earthquakes. In between, there are wide frequency ranges that can be searched for hidden signals.

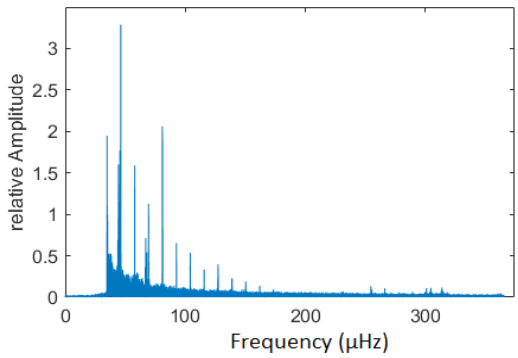

Fig 3: Typical spectrum of the high-pass filtered data series of a superconducting gravimeter in Europe.

Acknowledgements

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Herbert Weidner (2021-02-01)