Initially problems in observing 0S0.

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Abstract: Superconducting gravimeters are overloaded by strong earthquakes and stop the measurement. Here it is shown that, in the first hours after restart, most of the SG deliver erroneous data, which prevents an accurate frequency measurement. Avoiding this disturbed region, the frequency can be determined much more accurately than before.

Introduction

After earthquakes, the Earth vibrates like a bell at different frequencies and the whole set of different eigenfrequencies is recorded by various instruments. After large magnitudes, the extremely sensitive superconducting gravimeters (SG) are normally overloaded and provide no meaningful data for several hours. Some spectral lines as ${}_0S_0$ can be observed for months, others like ${}_0S_5$ are strongly damped by friction within the earth. They are difficult to analyze because the amplitude is already significantly reduced when the SG resume their operation.

The main reason for this study was to find the source of the peculiar frequency reduction of the ${}_0S_0$ oscillation (near 814.66 µHz) during the first 100 hours of strong earthquakes[1]. A possible cause could be a putative strong coupling to the higher-frequency oscillation ${}_0S_5$ (near 840 µHz) causing a frequency shift [2].

The underlying data of this examination were measured by a net of about twenty SG distributed over all continents, the data are collected in the Global Geodynamic Project [3].

The Preparation of the data

All available CORMIN-data of SG-stations were bundled into separate two-year-clusters like CB1011 or ST1011. To prevent intermodulation by numeric overload of the mathematical coprocessor inside the computer, the very strong spectral lines around 22 µHz were attenuated by narrow notch filters[4]. After decimating the sampling rate to 1/360 s, the signal was multiplied by a sine wave of selectable frequency ($f_{BFO} \approx 814.66$ µHz) and phase. Then, the data were low-pass filtered with a bandwidth of 50 µHz and the sampling time was increased to 30 minutes.

This *zero-beat* method shifts the "high frequency" information around f_{BFO} to much lower frequencies, where they can be analyzed more precisely. In particular, the adjacent channel interference by ${}_0S_5$ can be overcome simply because of the relative frequency spacing is much larger than before.

For all SG-records of the year 2011, the unique starting time 10350 hours past 1 Jan 2010 was defined, well before the actual time of the earthquake. During the following hours, there are no reliable data due to overload of the instrumentation

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until many hours later, the measurements start again. It does not matter that this data gap has different length at each station – annoying are the strange errors after restart of the records that are not seen at the first glance.

Another problem is caused by the unavoidable filtering of the data. After the data gap following a strong earthquake, the measured amplitudes suddenly rise to high values. Each electronic filter is responding with a step response distorting the subsequent data. Additional errors may be caused by the above mentioned ${}_0S_5$ because their frequencies are just above the analyzed ${}_0S_0$.

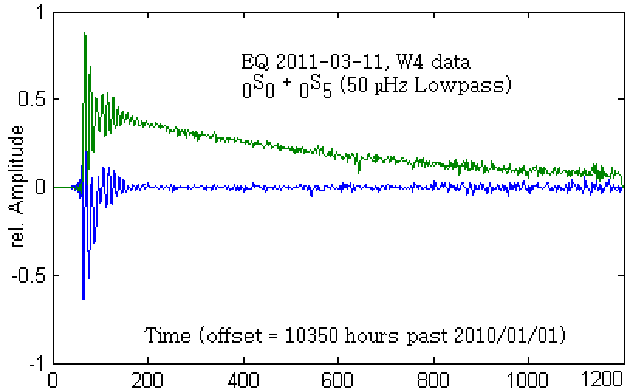
In order to minimize any such disorders, a trick was used, which is possible only with stored records and seldom used in real-time problems: The chronological order of the data was reversed, processed and reversed again. The data processing begins 1200 hours after the earthquake and ends a few hours after the earthquake. This time-reversal of the investigation period (IP) ensures that first small amplitudes are processed, producing a small, negligible step response. The slow decrease of the amplitude of damped oscillations now appears as a gentle rise, which produces no detectable step response.

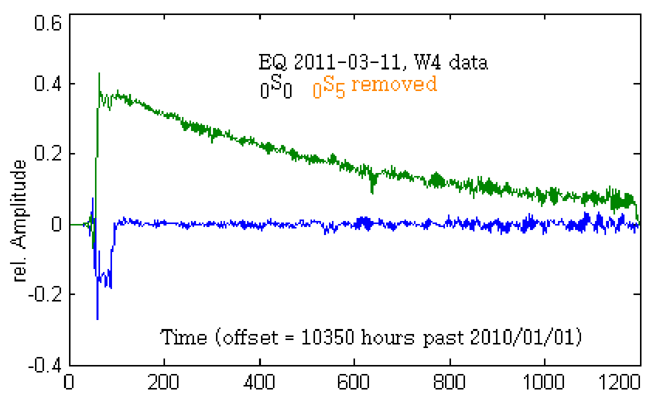
When the record ends abruptly at the end of the reversed IP (several hours past the earthquake), the resulting step response can be ignored because it is not based on measured data. In this way, interesting details at the beginning of the data recording (shortly after the earthquake) are distorted as little as possible. This is a good opportunity to reveal systematic errors of the measuring instruments.

${}_0S_0 \pm {}_0S_5$ indicates faulty data

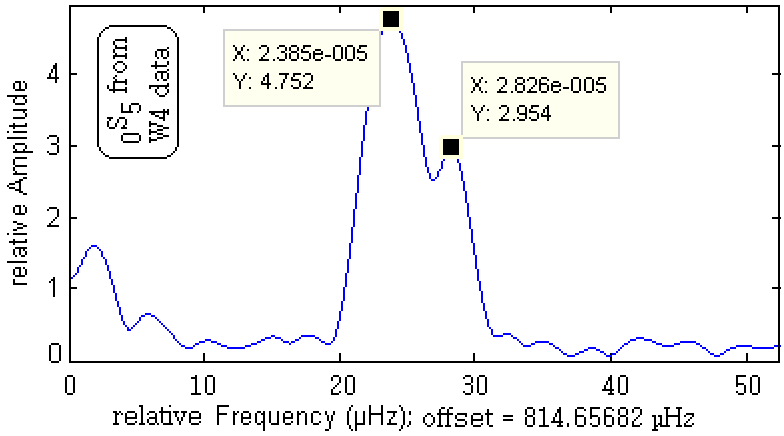
The left image shows a 1,200-hour long period of SG data taken by the station W4. The blue curve the result of $(Signal)\cdot\cos(2\pi t\cdot 814.65682\,\mu Hz+3.7867)$ and should be zero all the time, because frequency and phase are "locked in". The green curve is the time dependent amplitude and should show an exponential decay. That's exactly the way, how a lock-in amplifier detects weak signals in a noisy data stream.

Three days after the earthquake this station provides data, wherein the amplitude of the oscillation ${}_0S_5$ predominates. Within a few days, this mode is weakened by the internal friction of the earth and thus can no longer be detected. There remains only the oscillation ${}_0S_0$.



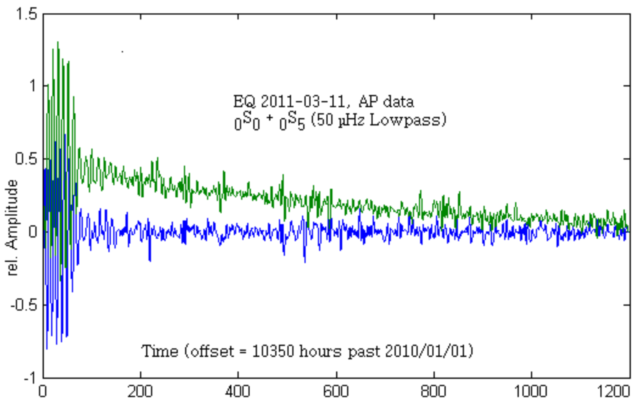


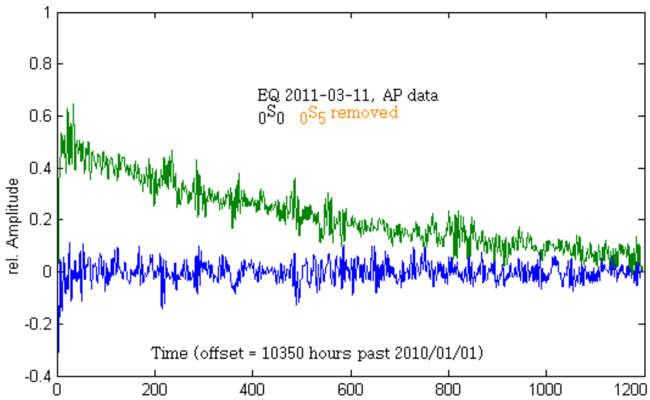
Between the time marks 50 hours and 200 hours, there is a superimposed wave packet with a strangely deformed envelope. The spectrum was calculated by FFT and is shown in the following image. The frequency resolution is bad because the interval is very short. Adding the reference frequency of the zero-beat method (f_{BFO} = 814.65682 µHz), we can roughly estimate the resonance frequencies of ${}_0S_5$. 838.5114 µHz and 842.9195 µHz. The small peak at 2 µHz is caused by a faulty modulation of ${}_0S_0$, it did not exist with correct data. (It should be noted here that other stations measure different frequencies of ${}_0S_5$ and the spectrum is shaped differently. This detail will not be discussed here.)



Suppressing these two disturbing frequencies between 20 µHz and 31 µHz by a narrow-band notch filter, the right picture *above* shows something surprising. After overload, the SG in Wettzell provides incorrect data corresponding to a phase shift of roughly 21 degrees. At the frequency 814.66 µHz, this phase shift corresponds to a data shift in the CORMIN records by almost 72 seconds.

During a time span of approximately 40 hours, eleven of the thirteen SG records show this error, and magnitude and sign of the error angle match. The phenomenon is neither a property of ${}_0S_0$ nor caused by the evaluation program used here. The stations AP and KA do not generate this kind of error, as the following pictures show.





The station AP can apparently handle much larger signal amplitudes and continues scanning even under strong earthquakes. Unfortunately, the noise level is so high that a further analysis of the first few hours after an earthquake will be difficult.

Thus the cause of error in the measurements in [1] is detected. The unexplainable increase in frequency during the first week following a powerful earthquake is a result of data errors. The above analysis shows that these errors are either caused by (identical?) technical defects of most SG or by errors in the program which converts the raw data into the CORMIN files.

There is no evidence of a change in frequency during the first few hours past a strong earthquake. A frequency-pulling by interaction of ${}_0S_0$ with the neighboring ${}_0S_5$ mode can be ruled out.

Frequency measurements

The measurement of frequency with the *zero-beat* method is based on minimizing the average and slope of the product $(Signal)\cdot\cos(2\pi f t+\varphi)$ in a predetermined interval, called integration period (IP). The only variable parameter is the length of the interval.

Since the initial region of the above-specified interval is unsuitable for the zero-beat method, the frequency measurement must not start earlier than 200 hours after the earthquake.

2011

Analyzed files: AP, CB, H3, KA, M1, M2, MB, MC, PE, ST, SU, W3, W4. To minimize the influence of random noise, in each of the 13 records, the frequency was measured with five different IPs. The shortest IP ranges from 400 h to 1000 h past the starting time 10350 hours past 1 Jan 2010. The longest IP ranges from 200 h to 1200 h.

The average of 65 measurements was determined by the jackknife method and is 814.656815 ± 0.000085 µHz.

2010

Analyzed files: AP, B1, B2, CB, H3, KA, M1, M2, MB, PE, SU, W1, W2. The data from MC and ST had to be omitted because they were much too noisy. To minimize the influence of random noise, in each of the 13 records, the frequency was measured with five different IPs. A starting time 1370 hours past 1 Jan 2010 was defined. The shortest IP ranges from 400 h to 1000 h. The longest IP ranges from 200 h to 1200 h.

The average of 65 measurements was determined by the jackknife method and is 814.659907 ± 0.000133 µHz.

2004

Analyzed files: CB, H1, H2, KA, M1, M2, MA, MB, MC, S1, S2, ST, W1, W2. To minimize the influence of random noise, in each of the 14 records, the frequency was measured with five different IPs. A starting time 8645 hours past 1 Jan 2004 was defined. The shortest IP ranges from 400 h to 1000 h. The longest IP ranges from 200 h to 1200 h.

The average of 70 measurements was determined by the jackknife method and is 814.657014 ± 0.0000611 µHz.

All error bounds are much narrower than that in [2],[5] and [6].

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