# Do superconducting gravimeters react to gravitational waves?

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**Abstract**: In the spectrum of data from superconducting gravimeters, a spectral line at 240.1 µHz shows an unexpected frequency modulation, which may be an indication of an extraterrestial origin of the oscillation. Perhaps, the earth responds to GW of the galaxy nucleus of NGC 1530.

# Introduction

A gravitational wave can interact with matter by exciting vibrations of elastic bodies like the Earth. The dimensions of this huge test specimen with 12740 km diameter can hardly be exceeded in the near future. A network of highly sensitive superconducting gravimeters (SG) from the *Global Geodynamics Project* (GGP) is a great way to search for gravitational waves. SGs have no directivity or time limit in the astronomical sense and can measure for years without interruption. SGs can reliably measure frequencies in the range between a few µHz to more than 10 mHz. The GW of accelerated objects with several thousand solar masses are expected in this frequency range.

In 2003, the PSR J0737-3039 double-pulsar system with a cycle time of 8834.535 seconds was discovered[[1]][[2]], generating gravitational waves. The frequency of the GW of 226.384 µHz exceeds the measuring range of interferometers such as LIGO, but it could be measurable with superconducting gravimeters because the frequency lies in a quiet frequency range, far away from all intrinsic resonances of the terrestrial globe. Four years later followed the discovery of a similar system PSR J0348+0432[[3]], which generates GW with the frequency 226.002 µHz. For this reason, the gravimeter data of this frequency range have been thoroughly investigated. An enigmatic signal at 240.1 µHz has been detected, which is generated by an unknown source.

# Preparation of the data

In the data records published by the GGP, the main source of disturbance are the frequent earthquakes and the periodic deformation of the Earth's surface by the tides. It costs some effort to eliminate the interference generated thereby. After the elaborate development of suitable methods[[4]], it turned out that there are unexpected correlations in the noise floor of geographically far apart SG, which do not correspond to known resonances of the Earth and are no nonlinear combination frequencies of the tides.

The SG are not uniformly distributed on the surface of the Earth and due to the 24-hour rotation of the Earth in the wave field of the GW of each source, phase shifts of the signals are expected, which can hardly be estimated. Therefore, another way has been chosen to achieve some signal amplification: in Central Europe, there is a world-wide unique cluster of ten SG, whose signals should be approximately in-phase. Therefore, the data series of the stations Bad Homburg, Moxa, Medicina, Membach, Strasbourg, Wettzell and Vienna were individually cleaned of disturbances and then added. A comparison shows that this significantly improves the signal-to-noise ratio of all spectral lines in the frequency range below 2 mHz. All subsequent studies are based on data recorded in the years 2004 to 2007.

Normally SG measure the value of gravitation once every second. Before publishing the records, the data volume is reduced by the factor 60 and short gaps are filled by synthetic tide data. After many such CORMIN data records were combined into a single chain, the strong tide signals below 82 µHz were cleared by selective compensation[[4]]. This reduces the noise level to 1 nm/s² without increasing the noise level. The influence of the variable air mass over the gravimeter is ignored because it raises the noise level in the range around 200 µHz. It is very time-consuming to discover the numerous inserted synthetic data and replace it with zeros in order to improve the SNR.

In the present case, it has been possible to reduce the noise level to such an extent that the otherwise

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barely detectable resonance at 196.4 µHz (T = 24 h / 17) becomes visible. The spectral line at 240.1 µHz has no known geophysical cause and is subsequently analyzed.

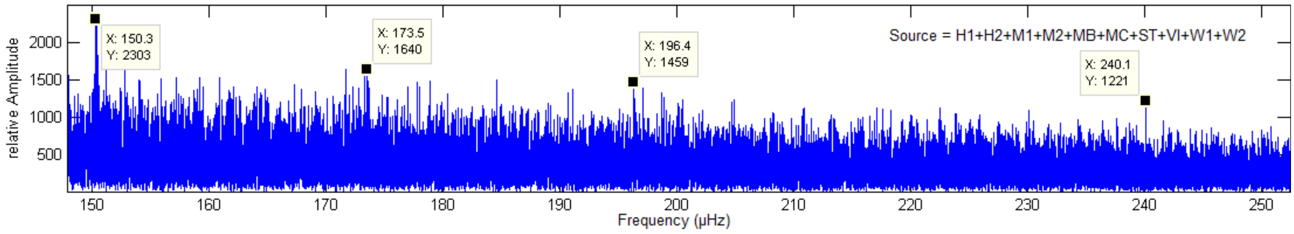


*Fig 1: Partial spectrum of gravitational data measured in Central Europe between 2004-01-01 and 2007-12-31. First, the tides and perturbations were removed from each record of the ten specified SG stations, then the data series were added to improve the SNR.*

# The carrier frequency

Fig. 2 shows that the spectral line at 240.1 µHz clearly exceeds the noise level and has an unusual shape with a sharp cut in the middle. Earlier studies of other spectral lines have shown that the division may be caused by a phase reversal of the underlying vibration. Since it is unclear whether it is a modulated oscillation, it makes sense first to filter out all sidebands and to focus exclusively on the central frequency. By isolating each half of the twin line by narrowband filters, one can determine the amplitude as a function of time of both parts over the entire period from 2004 to 2007. The two envelopes agree so precisely that a common origin must be assumed.

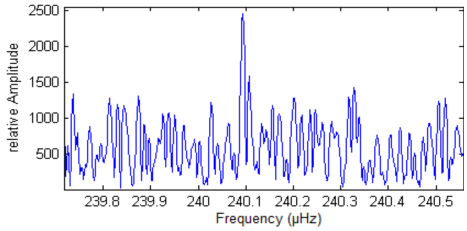


*Fig 2: Enlarged part of figure 1*

The frequency spacing of the two peaks is 0.015 µHz, indicating that there exists a characteristic period of about 770 days. This is confirmed by the envelope shown in figure 3. Before, the signal passed through a 0.06 µHz wide bandpass filter to reduce the noise. Because the bandpass filter suppresses any distant sideband frequencies, no rapid amplitude changes can be visualized. The average frequency of the first oscillation package between 2004-01-01 and end of 2005 is 240.097 µHz, the spectrum has a single peak. The same holds for the following oscillation package from 2006 till end of 2007. At this stage of the investigation, it is unclear why it turns into a double line when calculating the spectrum over the entire four-year period.

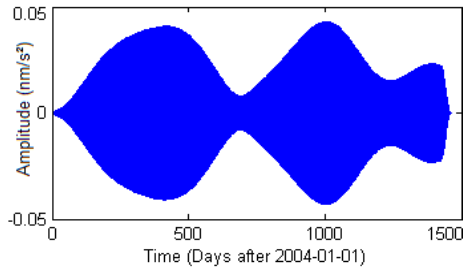


*Fig 3: The oscillation at 240.1 µHz shows slow amplitude fluctuations, if the noise in the environment of is suppressed by a narrow-band filter.*

# Measurement of the average frequency

As preparation for further analysis, the signal frequency was down-converted to the IF = 3.1 µHz (reason in the next section). At this low frequency, the duration of each oscillation can be precisely determined by counting and interpolating. It can be seen that the oscillation period slowly decreases.

Over the 4-year period considered, the oscillation period of the IF shortens from 322476 seconds to 321292 seconds. Since previously 237 µHz was subtracted (superhet principle), this means an increase of the signal frequency from 240.1010 µHz to 240.1124 µHz in a 4-year period. Maybe, the energy loss is caused by the emission of a gravitational wave.

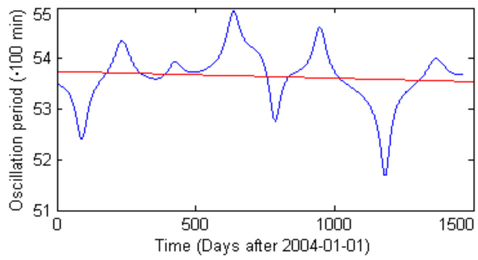


*Fig 4: The measurement of the period duration takes place by counting the sampling intervals (6000 s) between the zero crossings.*

Further clarity brings the "direct conversion", ie the multiplication with a reference oscillation (constant frequency). If this matches exactly with the signal frequency, the product is either always positive or always negative, provided that the phase is chosen correctly.

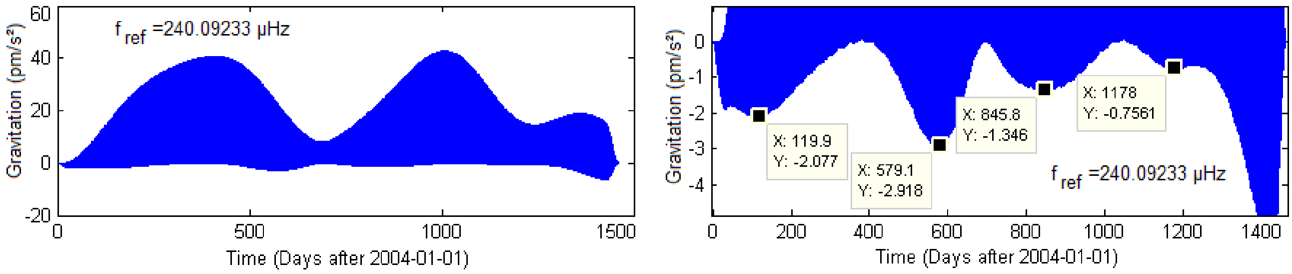


*Fig 5: The left picture shows result of multiplication of the signal with the reference frequency 240.09233 µHz. This is the stronger of the two peaks at 240.1 µHz. The picture on the right shows an enlarged view of the negative values, which are obviously no noise.*

In the left part of figure 5 you can see the result of the direct conversion. Over the entire four-year period, the signal has an amazing frequency and phase consistency, because the product hardly takes negative values. Known geophysical signals show a much more restless phase course. Examining the negative portion more precisely (right part in figure 5), one recognizes an amazing regularity: the gravitational force on the surface of the terrestrial globe changes approximately in the annual rhythm. Due to the poor signal-to-noise ratio, the distances between the minima are somewhat irregular.

To avoid misunderstandings: Figure 5 shows no slow oscillations of the earth, but slow changes of amplitude and phase of the 240.1 µHz oscillation, whose source is still unclear. There is no known physical process that could cause this vibration within the earth.

Probably the best explanation of this frequency modulation is the assumption that the spectral line at 240.1 µHz is generated by an extraterrestrial source. The doppler effect shifts the frequency due to the high orbital velocity of the Earth on its way around the sun (about 30 km/s).

# The frequency modulation

In order to check a possible frequency modulation of the oscillation at 240.1 µHz, the bandwidth must be carefully selected. A too small bandwidth will cause a strong signal distortion and the modulation gets suppressed; if the value is too large, the modulation may disappear in the noise. The orbital period of the Earth around the sun corresponds to a modulation frequency of 31.69 nHz. To prove this frequency, the bandwidth must exceed 65 nHz, so as not to suppress the sidebands. In addition, the middle frequency (still) is not exactly known. Based on these considerations, one should choose a larger bandwidth than absolutely necessary.

The oscillation frequency is 8000 times higher than the modulation frequency. A bandpass filter with such a high quality factor ist hard to realize. This task is simplified by reducing the carrier frequency to a much lower value. In the telecommunications sector, this frequency shift takes place with the proven superhet method. In this study, the signal frequency was down-converted to the IF-frequency 3.1 µHz before passing through a narrow bandpass filter. Then, it is easy to determine the duration of each oscillation to get the instantaneous frequency as a function of time and the frequency deviation can be read off directly (Red curve in figure 6). The amplitude of the oscillation does not influence the result, we only measure frequency changes.

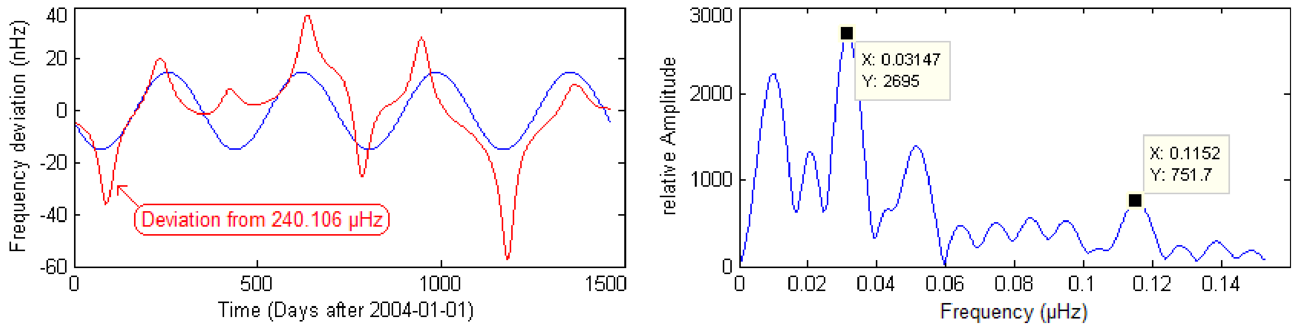


*Fig 6: In the left image, the red curve shows the deviation of the measured instantaneous frequency from the mean value of the IF (3.1 µHz). The bandwidth of the IF filter was set to 130 nHz. The blue curve shows the expected frequency change produced by the doppler effect (best fit). The frequency is given by the orbital period of the earth and the amplitude and phase have been optimized so that the deviation between the two curves is minimal. The right image shows the spectrum of the measured instantaneous frequency.*

Because of the poor signal-to-noise ratio, the frequency often deviates noticeably from the mean, but the deviations are not random, as the spectrum shows (right part of figure 6). Particularly pronounced is the frequency 31.47 nHz, which corresponds to a period of 368 days.

If the signal source of the 240.106 µHz oscillation is located very far away from the Earth, the Doppler effect should cause a sinusoidal frequency modulation with the period 365.25 days because of the high orbit speed of the Earth around the sun. Therefore, the next task is to optimize the amplitude and phase of a 31.69 nHz oscillation (blue curve in figure 6, left part) so that the difference between blue and red curves gets particularly small. The results depend slightly on the bandwidth of the IF filter and are shown in the table below. As already mentioned, the bandwidth must exceed 65 nHz in order not to suppress the sidebands of the frequency modulation. If a bandwidth of more than 170 nHz is selected, the modulation is hardly recognizable due to the reduced signal-to-noise ratio. Then the data gaps after the numerous earthquakes falsify the results more and more.

| Bandwidth (nHz) | Phase | Max. frequency deviation (nHz) | Mean frequency (µHz) |
|---|---|---|---|
| 100 | 1.7681 | 13.812 | 240.1061 |
| 110 | 1.8046 | 14.550 | 240.1064 |
| 120 | 1.8416 | 14.990 | 240.1067 |
| 130 | 1.8776 | 14.899 | 240.1066 |
| 140 | 1.8916 | 14.321 | 240.1059 |
| 150 | 1.9275 | 14.033 | 240.1056 |
| 160 | 1.9940 | 14.520 | 240.1058 |
| Average | 1.8721 ± 0.0287 | 14.446 ± 0.162 | 240.10616 ± 0.00016 |

The average values were calculated using the jackknife method.

# Position of the source

So far, the results can be summarized in a formula. The measurable frequency of the oscillation discussed here fluctuates periodically around the mean $f_0 = 240.106 \pm 0.00016\,\mu Hz$. The deviation depends on the season and can be described by formula

$$\Delta f_{FM} = 14.446 \cdot \cos(2\pi \cdot 31.68809\, nHz \cdot t + 1.8721)\, nHz \quad .$$

The time t=0 starts on 2004-01-01 at 0 o'clock.

If the distance of the source of the oscillation is much larger than the diameter of the orbit around the sun, it makes sense to determine the position with respect to the ecliptic. If the source is in the ecliptic, the maximum frequency shift would be

$$\Delta f_{max} = f_0 \sqrt{\frac{c+v}{c-v}} = 240.1\,\mu Hz \cdot \sqrt{\frac{3 \cdot 10^8 + 3 \cdot 10^4}{3 \cdot 10^8 - 3 \cdot 10^4}} = 24\,nHz$$

Since the measured value is about half as large, the source lies at the angle α above or below the ecliptic. The formula

$$\frac{f_0 + \Delta f_{FM}}{f_0} = \frac{\sqrt{1 - v^2/c^2}}{1 - \cos\alpha \cdot v/c}$$ yields the ecliptic latitude of the source: α = ± 53.0º.

The ecliptic longitude of the source can be calculated from the phase shift 1.8721 rad. The largest redshift is measured 73.5 days after January 1, the largest blueshift 256 days after January 1 (see figure 6). On these days, the earth moves approximately parallel to the line of sight. It is irrelevant that the earth rotates, as the gravimeters have no directivity.

The calculation[5][6] gives the ecliptic longitude 81.02º.

# Possible Sources of Gravitational Waves

It is unlikely that the signal source is near the center of the Milky Way because this direction is far from the target direction. There are also no suspicious sources in our galaxy. Are there any interesting objects in both directions?

Ecliptic longitude = 81.02º, ecliptic latitude = +53.0º

- NGC 1530 is a barred spiral galaxy, one of the largest in the northern sky with a mass inflow into the core and a massive star formation in the central region[7][8]. Distance = 115 million light years. Very special!
- NGC1343 is also a barred spiral galaxy with a mass inflow into the core. Distance = 96 million light years.

Ecliptic longitude = 81.02º, ecliptic latitude = -53.0º

- NGC1532 is a barred spiral galaxy in the southern sky, 50 million light years away.
- NGC 1537 is an elliptical galaxy, 58 million light years away.

The present study provides no further indications as to whether one of the galaxies mentioned is to be preferred.

One of these objects may contain two sufficiently massive objects that rotate rapidly around a common center of gravity. Then the brightness of a small area of the respective galaxy could fluctuate in the rhythm of about 2.3 hours. That could be checked, if instead of the usual continuous exposure a sequence of many individual shots is generated. An integration period of about ten minutes may be appropriate to demonstrate a regular brightness variation in a small area of the surface.

# Final remarks

From an astronomical point of view, all previously installed SG have a disadvantage: they are not acoustically isolated from the earth and therefore react very strongly to shocks and earthquakes. If you only want to measure the local gravitational value and lower the noise to values below 10 pm / $s^2$, the gravimeter must be mounted vibration-free. Every effort must be made to ensure that rapid ground movements can not influence the readings. Only then is there a chance to clearly prove the earth's reaction to the extremely weak GW. The traditional way of mounting the expensive SG is counterproductive.

## Acknowledge

Thanks to David Crossley for initiating the Global Geodynamics Project (GGP) and thanks to Ralf Kotulla and Tom Fliege for the quick completion of the astronomical position calculations. Thanks to the geophysicists at the superconducting gravimeters for many years of patience in collecting data. Thanks the IGETS data base at GFZ Potsdam for storing the data.

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