The search for gravitational waves
Fundamentals of reception technology

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Summary: In order to detect and decode the phase-modulated signals of gravitational waves in noise, you need an antenna and a receiver in the μHz range with special properties. The necessary technology is described in detail.

1 Introduction

107 years ago, Albert Einstein claimed that certain astronomical events produce gravitational waves. These were first detected 99 years later, but only in the form of short-term wave packets with limited significance. Astronomers want much more information, which can only be obtained by studying continuous, i.e. long-lasting, gravitational waves (GW). Although these GW undoubtedly exist, it has not yet been possible to detect continuous signals with the known properties, despite huge antennas and enormous human effort. The reason could be that scientists only evaluate signals from the LIGO and VIRGO interferometers because they believe that only these are sensitive enough. The lower limit frequency of these antennas is 20 Hz and no one is sure whether transmitters with significant power exist at higher frequencies, such as pulsars with high mountains. And they try to detect continuous signals with broadband receivers and with statistical methods (Markov chains), even though the frequencies of possible sources are known very precisely.

In radio technology, extremely weak signals from distant space probes such as Voyager are detected using receivers that are as narrow as possible in order to minimize noise. GPS could not be received with 'impossible' antennas without exploiting the properties of the known modulation.

And other questions are asked: In which frequency range do the most powerful sources transmit, how far away are they? Are there good receivers and antennas?

What we know about GW so far is that binary stars with orbital periods of a few days produce GW in the frequency range around 10μHz, the radiated power is likely to be around 10^{30} watts – that is more than the sun emits in electromagnetic waves. Since stars can be easily seen at a distance of about a hundred light years, GW should also be easy to measure here. A Software Defined Receiver (SDR) can receive this frequency range and is extremely sensitive.

The only problem is the antenna: It has to convert mechanical deformations into an electrical signal because, according to theory, GW are quadrupole waves that can compress and stretch the measurable distance between two points. GW are transverse waves and therefore an antenna should be oriented transversely to the direction of propagation of the GW. In contrast to electromagnetic waves, every conceivable antenna is a far too short solution, as the wavelength is on the order of millions of kilometers. Will there ever be resonant antennas that would have to be about the size of the solar system?

So far, some antenna designs have already been examined:

- Fifty-five years ago, Weber attempted to build resonant antennas using metal cylinders. However, it is unclear whether sources exist that produce GW at high frequencies around 1500 Hz. These attempts were finally stopped 20 years ago due to failure.
- Interferometers are significantly more sensitive and also react to slightly lower frequencies. In 2016, LIGO was able to detect short-term signals. Since then, attempts have been made (without success) to detect continuous GW using these antennas. It is possible that sources in the range $f_{GW} > 20$ Hz generally only have low power.
- An antenna for extremely long wavelengths is planned. The aim is to launch the LISA interferometer with a side length of 2.5 million km in 10 years at the earliest, with which it is hoped to detect low-frequency GW.
- Nobody wants to believe that the earth itself or the atmosphere could also be a useful antenna. This view can only be corrected through experiments.

In long series of tests with different antennas and extremely narrow-band receivers, I received signals at low frequencies around 10 μHz that have all the hallmarks of GW (Section 3). I will describe the technique below in the hope that others will be more successful with improved methods.

My first idea was: GW is measured with gravimeters. These are extremely sensitive and numerous because geophysicists use them in earthquake research (the measurements are freely accessible). The evaluation electronics are optimized for the frequency range 10 μHz to 0.5 Hz and initial tests showed that many signals with GW properties can be found in this range (see section 3). The results are not satisfactory because frequent earthquakes disturb the gravimeters. Therefore, other antennas were investigated. Geophysicists reduce the strong noise of the gravimeters by adding the value of the air pressure. A comparison shows that the spectra of the Gravimeters clearly differ from the spectrum of air pressure; in particular, air pressure hardly reacts to earthquakes. Both contain both known and unexplained spectral lines [1]. Could this be GW?

2 The atmosphere as an antenna for GW

Using strange antennas, Marconi succeeded in bridging the Atlantic with radio waves. It was only over the course of many years that people learned to build effective antennas. This will be no different with GW: First you have to learn to receive GW reproducibly, then antennas can be optimized. It remains to be seen whether compact antennas similar to ferrite antennas can be implemented.

The air pressure is not measured continuously, but at fixed intervals of, for example, one hour. The reciprocal of the sampling interval t_s is called the sampling frequency f_s. If you want to measure continuous waves of the frequency f_{GW}, two requirements must be met: Before the measurement, the signal mixture must pass through an analog low-pass filter with the cutoff frequency $0.5 \cdot f_s$ and the sampling frequency must be sufficiently high ($f_s > 2 \cdot f_{GW}$). If these two conditions are violated, the measured frequencies will be ambiguous. (https://en.wikipedia.org/wiki/Undersampling)

Several details stand out in figure 1:

- The noise amplitude near $f \approx 1$ μHz is about 10^7 times larger than at $f \approx 100$ μHz. So it is not the frequently observed $1/f$ noise. Is it even noise? My suspicion: We see GW emitted by (still) unknown binary stars. Astronomers estimate that our galaxy hosts at least 10^6 binary systems, most of them emitting in this frequency range.
- The amplitude difference between the left and right edges of the spectrum can be used to advantage: If you limit all investigations to the range $f < 40$ μHz, you can ignore the unsuppressed frequency components above 140 μHz, because they are sufficiently weak. Then it doesn't matter whether the DWD uses an analog low pass in front of the sampler.

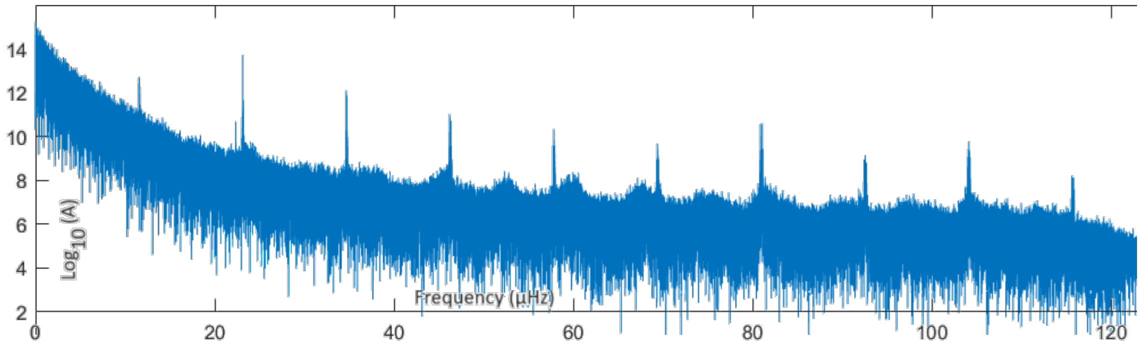

Figure 1): *Spectrum of air pressure in Germany. The database is based on the average air pressure between the years 2000 and 2020. With one measurement per hour, the spectrum of the signal mixture is folded into the frequency range* $0 < f < 139$ *µHz. The striking maxima are explained in the text.*

- One should not look for GW in the vicinity of multiples of $f \approx 11.57$ µHz $= 1/(24$ hours). The period of oscillation suggests that the sun is somehow involved with these striking resonances in the atmosphere.
- A special feature is the lonely peak at 22.3643 µHz. At this frequency the moon deforms the earth and the atmosphere (tides). The moon, the sun and the planets generate further, much weaker resonance frequencies, which are precisely known and tabulated in [3]. These known 13,000 frequencies do not interfere with the search for GW in any way because the amplitudes are usually very small, because their frequencies do not change and because they are not phase modulated.

In the records of weather stations located far apart one can find identical spectral lines with properties of GW (see section 3). Results so far suggest that the atmosphere responds to GW just like any other object and is therefore a suitable antenna. The amplitude of the signals is small and the signal-to-noise ratio (SNR) is not sufficient (without pretreatment) for precise measurements in the frequency range around 10 µHz.

The DWD stores air pressure data on its homepage [2], which can be used as a free data source after some preliminary work. In order to reduce the influence of local peculiarities and data gaps from individual weather stations, the measured values of as many barometers as possible are added together, which are distributed across Germany and have been in operation almost continuously for at least ten years. In the period 2000 to 2009, 64 data chains were found, in the period 2010 to 2019 only 51 data chains. Because the wavelength of the GW sought is at least a factor of 10^6 larger than the mutual distances of the barometers, all instruments react to the GW in phase. This coherent addition of many records improves the SNR and makes spectral lines visible that disappear in the noise when analyzing just one data chain.

A 20-year period is necessary to achieve a frequency resolution Δf better than 1 nHz. Filters with this low bandwidth require a lot of time to settle down. According to Küpfmüller, the minimum time applies[4]

$$T_{min} \cdot \Delta f \geq 0.5 \tag{1}$$

The disturbing environment of weak signals is blocked out using extremely narrow-band filters. Windowed-sinc filters with 10^5 nodes and 0.5 nHz bandwidth deliver good results. Although IIR filters require less calculation time, they are hardly suitable because they produce phase distortions.

3 Properties of continuous GW

Presumably no continuous GW is amplitude modulated on a time scale of less than a thousand years. Verification is difficult because the SNR is rarely sufficient to detect and demodulate AM.

Each GW is phase modulated with at least one frequency as the antenna orbits the sun. Let's assume that a GW source is located near the plane of the ecliptic. Then the reception frequency f_{GW} is lower than the average value for half a year because the distance between source and earth increases (redshift). In the next half year, f_{GW} will be higher than the average value. Since the Earth's orbit is almost circular, a sinusoidal phase modulation with the frequency $f_{orbit} = 31.688$ nHz is a necessary confirmation that the GW is *not* generated in the solar system. This PM is decoded in the same way as all other PMs.

In 365 days, the Earth orbits the Sun, which is 150×10^9 m away. The calculated orbital speed is 30 km/s – much smaller than the speed of light. The maximum frequency shift as a result of the Doppler effect is

$$\Delta f = f_{GW} \cdot \left(\sqrt{\frac{c + v_{orbit}}{c - v_{orbit}}} - 1 \right) \approx f_{GW} \cdot \frac{v_{orbit}}{c} \approx \frac{f_{GW}}{10000}. \quad (2)$$

If you receive a GW of frequency $f_{GW} = 10\ \mu$Hz, you should observe a periodic frequency modulation with a frequency deviation of 1 nHz. This is as large as the width of the spectral line and is therefore just measurable. I've already measured a few GW and in every case the frequency deviation was significantly larger, sometimes even by a factor of 100. Despite a thorough search, I couldn't find any errors.

A binary star system compensates for the constant loss of energy by rotating ever faster. This can be noticed by a small frequency drift of f_{GW}. As a result, the distance between the stars decreases and at some point they merge.

Astronomers suspect that most binary stars have multiple planets orbiting them. Even a very light planet causes a phase modulation with its orbital frequency. You (usually) know neither the number of planets nor their periods, but you have to expect a multiply modulated signal.

4 Phase Modulation (PM)

It doesn't work without mathematics. The ansatz

$$y = A_{GW} \cdot sin(2\pi t(f_{GW} + kt) + \phi_{GW} + a_{planet} \cdot sin(2\pi t f_{planet} + \phi_{planet})) \quad (3)$$

describes a phase-modulated GW when there is a single planet. There is no physical reason to discuss amplitude or frequency modulation of a GW. The parameters in the ansatz mean:
– y is the output voltage of the oscillator
– A_{GW} is the amplitude of the GW (not very interesting)
– t is the time
– k is the linear frequency drift (= frequency change per year)
– ϕ_{GW} indicates when our distance to the source increases or decreases
– a_{planet} is the modulation index of the PM, an important measurement result
– f_{planet} is the orbital frequency of the planet
– ϕ_{planet} indicates when the planet is in front of or behind the binary star

The formula 3 is the basis of the SDR (section 5). Each modulation creates sidebands, i.e. spectral lines next to f_{GW} that transport energy. Logical consequence for PM and FM: The amplitude of the carrier frequency f_{GW} decreases because the total energy of the GW remains constant. At certain values of the modulation index – for example $a_{planet} = 2.4$

– the carrier frequency can no longer be measured. Then the GW has not disappeared, just the search becomes more complicated. Since one does not know whether one of the numerous planets causes an unfavorable modulation index, it is usually pointless to look for strong spectral lines (figure 2).

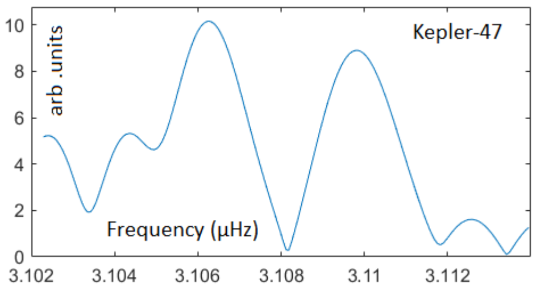

Figure 2): *Spectrum of the mean air pressure in Germany. The GW of Kepler-47 should be at* $f_{GW} = 3.108\ \mu Hz$*, where the amplitude is particularly small. Whether the almost symmetrical structure is generated by a PM with* $f \approx 1.9\ nHz$ *can only be known after the signal has been demodulated.*

An example shows how confusing the spectrum of a GW can become. Based on previous measurements, the following realistic parameters are preset:

- $f_{GW} = 10\ \mu$Hz, SNR = 10, no other GW sources in the vicinity of f_{GW}!
- Planet-a: $f_1 = 4$ nHz, $a_1 = 2.4$;
- Planet-b: $f_2 = 60$ nHz, $a_2 = 3.4$;
- Planet-c: $f_3 = 40$ nHz, $a_3 = 1$;
- Planet-d: $f_4 = 13$ nHz, $a_4 = 2$;
- Planet-e: $f_5 = 1.3$ nHz, $a_5 = 3$;

Figure 3 shows step by step how the spectrum broadens and how the SNR deteriorates as more and more planets orbit the GW source. With ten planets, the broadband signal is barely distinguishable from noise. Since there are several million binary stars in our galaxy, the spectra will overlap each other. Then it is difficult to determine which spectral line belongs to which GW.

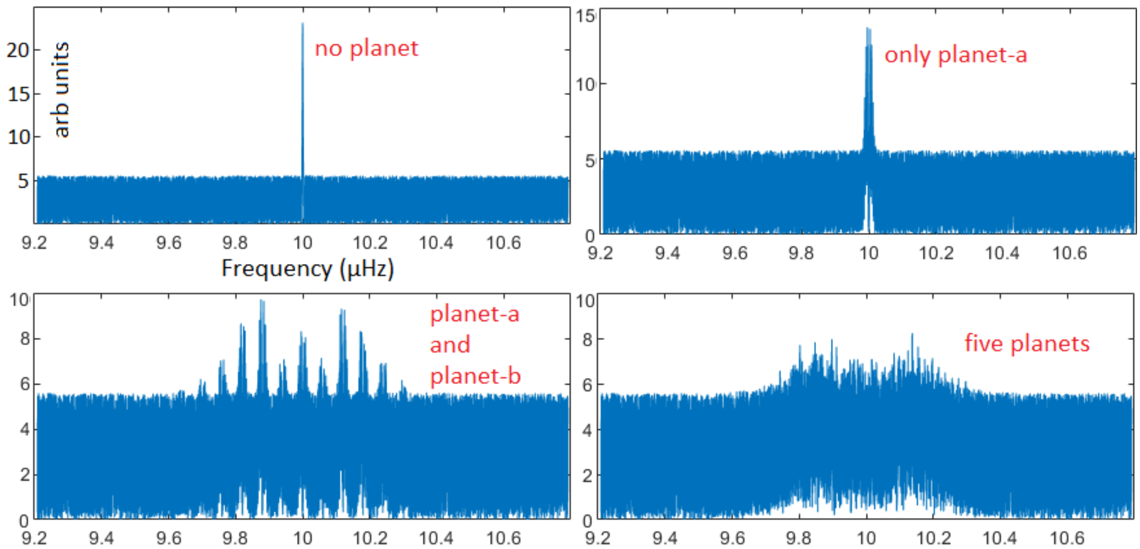

Figure 3): *Multiplication of the number of spectral lines as more and more planets orbit a binary star. The planet with the highest orbital frequency determines the Carson bandwidth to be processed. Unrealistic assumption for all spectra: In the frequency range 9* $\mu Hz < f_{GW} < 11\ \mu Hz$ *there is a single binary system without frequency drift.*

PM and FM are closely related. Since the formulas can be converted into one another, the terms can be exchanged. The most important key figure is the modulation index $a = \Delta f / f_{mod}$, which for GW fits the equation 2. Δf is the frequency deviation, i.e. the largest deviation of the instantaneous frequency from the mean. Two examples explain the application:

- In FM broadcasting, music is transmitted on 100 MHz with the highest modulation frequency of 15 kHz. The frequency deviation must not exceed 75 kHz in order not to disturb the neighboring channel. This means $a < 5$. The transmission frequency therefore fluctuates in the range 99.925 $MHz < f <$ 100.075 MHz.
- If a binary star emits $f_{GW} = 10$ μHz and is orbited by an Earth-like planet, its orbital period could be about 400 days ($f_{orbit} = 30$ nHz) and the orbital speed could be about 30 km/s. Together with equation 2 this results in: $a = \Delta f / f_{mod} = 1\ nHz/30\ nHz \approx 0.033$. The transmission frequency therefore fluctuates in the range 9.999 $\mu Hz < f <$ 10.001 μHz. In addition, there is the PM that the Earth produces as it rotates around the sun.

In both cases the value of the carrier frequency is meaningless. In both cases it is impossible to measure the short-term extreme values of the instantaneous frequency because this would require too long a measurement period during which the frequency must be constant (compare equation 1).

5 The MSH Method

The topic of this section is how to decipher the PM of a GW. I was unable to demodulate GW's PM using digital signal processing (SDR) methods. Possible reasons: The SNR of a GW is much too low; the modulation index should be greater than 2; the demodulation program of an SDR is designed in such a way that it demodulates the entire modulation, which usually includes a large number of individual frequencies, in one step. You want to listen to music and not just a few selected frequencies. In addition, you cannot temporarily turn off the PM of the GW source to measure the carrier frequency. There is always uncertainty as to whether the GW you are looking for exists and whether you are searching on the right frequency.

The following observation led to a solution: A modulated signal occupies a certain bandwidth. In the case of PM, this is theoretically infinitely wide, but in practice it is sufficient to take into account the spectral lines within the Carson bandwidth $B = 2f_{mod}(a + 2)$. If you go below this bandwidth, the modulation becomes distorted and demodulation becomes problematic. Formally, the Carson formula applies for $a > 1$. A spectrum shows that at $a \ll 1$ the sideband lines $f_{GW} \pm f_{mod}$ do not disappear.

This is an important observation: to detect a *weak* phase modulation with a single frequency, three frequencies are sufficient: $f_{GW} - f_{mod}$, f_{GW} and $f_{GW} + f_{mod}$. The frequency range in between contains no information, only noise. A corresponding filter with three very narrow passbands is quickly constructed using digital signal processing and a search for planets with different values of f_{mod} provides surprising results:

- Each of the binary star systems examined so far has more than five planets. To put it precisely: Five well-reproducible modulation frequencies that are probably generated by planets.
- The amplitudes of the sidebands at $f_{GW} - f_{mod}$ and $f_{GW} + f_{mod}$ are much higher than expected (see section 4).
- They are so high that the comparison with the Bessel functions suggests that the modulation index is in the range $0.1 < a < 5$. (This is not about the interpretation of these large values, but about the reception technology.)
- Large values of a widen the Carson bandwidth to be processed. This requires filters with several narrow passbands per planet.

Side note: Weak modulations using the AM, FM and PM methods with f_{mod} would all produce the same spectrum. They only differ in the phase relationships of the sidebands, which cannot be seen in the spectrum. A useful demodulation method must therefore also evaluate the phases of the sidebands. The MSH process solves the problem.

These tasks can be easily solved with SDR, but with multiple planets the design of the filter becomes confusing. The problem is that the effective bandwidth increases (more slots) and the unwanted noise also increases. A short calculation shows: If a planet generates the modulation index $a = 3$, the corresponding spectrum consists of ten spectral lines because you have to take all of the bessel functions J_1 to J_5 into account. If the double star has ten planets, the IF filter must have 101 narrow passbands that allow too much noise to pass through. This is not a promising way to discover weak GW.

That's why the principle is changed: With a superheterodyne, the oscillator frequency is usually constant so that the modulation of the signal is transferred unchanged to the intermediate frequency. With a modified superheterodyne (MSH), the oscillator is modulated with the aim of a *constant* IF (figure 4). This can be easily monitored and it enables an IF filter with an extremely low bandwidth and has two advantages:

- The effective bandwidth is reduced by a factor of 101, which means that the amplitude of the disturbing noise drops by a factor of 10. The SNR can increase so much that signals below the noise level become visible.
- The total energy of the GW, previously distributed over 101 spectral lines, is concentrated in the central line at f_{GW}. To put it bluntly, you add up the many lines in figure 3, bottom right, and you get the original line at the top left again.

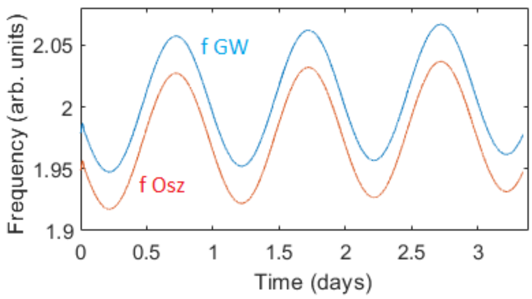

Figure 4): *The idea behind the MSH method: The frequency of the GW oscillates around an average value that slowly increases. If it is possible to generate an auxiliary frequency f_{Osz} with identical modulation, the difference $f_{GW} - f_{Osz} = f_{ZF}$ (= vertical distance between the two curves) is constant.*

Figure 5 shows the two-stage signal processing of the SDR. In this example, f_{GW} is first reduced by $f_{osz1} = 9$ μHz, as the subsequent decimation speeds up the calculations. If you are looking for extremely low-frequency GW, this stage is not necessary.

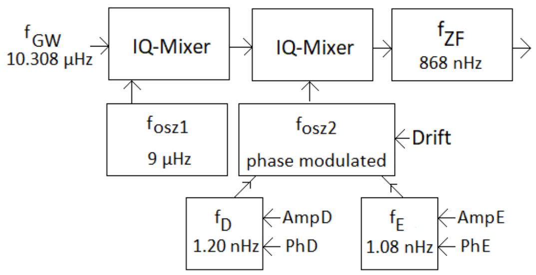

Figure 5): *Block diagram of the MSH method: f_{osz1} reduces the signal frequency without affecting the modulation. f_{osz2} mimics the PM of the signal to keep f_{ZF} constant. f_D and f_E are the modulation frequencies. At the top right output you measure the oscillation period and amplitude of f_{ZF}.*

A second oscillator f_{osz2} is phase-modulated by several inputs, which requires programming a separate auxiliary oscillator (f_D, f_E,..) for each planet of the binary star. The basis is the equation 3, which is extended accordingly. How to search for planets is the topic of section 8. If you succeed to modulate f_{osz2} in the same way as f_{GW}, f_{ZF} is constant and unmodulated and has a particularly large amplitude.

Because the MSH process eliminates all modulations, the bandwidth of the IF filter can be extremely narrow. Since you cannot create a perfectly rectangular pass curve, it is important that f_{ZF} lies exactly in the middle of the bandwidth. Therefore, f_{GW} must be tracked by a precise Automatic Frequency Control (AFC).

6 IQ Mixer

An IQ mixer is the perfect way to shift the frequency of a signal. It has no image frequencies and does not distort like the analog mixers of ancient times. Weaver described this standard building block to create SSB (figure 6). The process could also be called a *frequency-shifting band filter* because it shifts the center frequency of a signal mixture with the bandwidth B from f_{osz_1} to f_{osz_2}. B is twice as large as the cutoff frequency of the two low-pass filters.

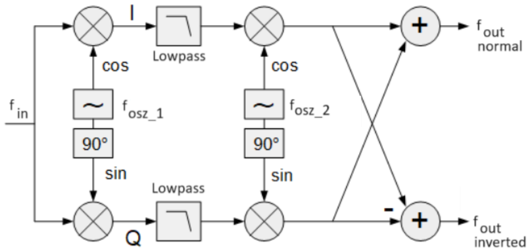

Figure 6): *Block diagram of the IQ mixer. The two low-pass filters must have the same cutoff frequency B. The frequency range* $f_{in} - B < f < f_{in} + B$ *is passed.*

In the age of analog technology, this circuit was rarely used because four double-symmetrical mixers were required. In digital technology, this means four multiplications of two data chains each. As a rule, you choose the upper signal output because a high input frequency then appears as a high output frequency (USB). The lower output may be omitted; the signal appears there in frequency reversal position (LSB). The following program lines show an IQ mixer in MATLAB.

```
function usb = Waever(y,Ts,f_ein,f_aus,B) % 0<B<0.5
L=length(y); j=(1:L)'*2*pi*f_ein*Ts; %generate f_osz1
ys=y.*sin(j); yc=y.*cos(j);
[b,a] = cheby1(6,0.01,B); %calculate lowpass
yc=filtfilt(b,a,yc); ys=filtfilt(b,a,ys);
j=(1:L)'*2*pi*f_aus*Ts; % generate f_osz2
ys=ys.*sin(j); yc=yc.*cos(j); usb=2*(yc+ys); % lsb=2*(yc-ys);
end
```

7 Inner and outer planets

The inner planets require little time to orbit the binary star and generate high modulation frequencies of f_{GW} (f_{mod} > 2 nHz), which the narrow IF band filter ($B \approx 0.4$ nHz) suppresses. This makes the search more difficult because you have to try 'blindly' all possible frequencies in the range 2 nHz $< f_{mod} <$ 500 nHz. Previous measurements mostly resulted in modulation indices $a > 1$, which – together with a high modulation frequency – requires a large Carson bandwidth. However, a large modulation index also means that there are many sideband components at a mutual distance of f_{mod} that transmit energy and weaken the carrier frequency.

As the MSH method iteratively succeeds in mimicking a planet's PM more and more closely, it weakens the sidebands and increases the amplitude of the carrier frequency. This makes the search criterion clear: You iterate f_{planet}, a_{planet} and ϕ_{planet} so that the amplitude of f_{ZF} becomes maximum.

The PM of far outer planets must be demodulated differently: They require many years to complete one orbit and modulate f_{GW} with such low frequencies that the sidebands lie within the bandwidth of the IF filter. As a result, f_{ZF} is not constant. You check this in the manner of a 'frequency counter': you determine and compare the times between successive zero crossings of f_{ZF}. Most of the time you get a wavy line and it is the job of the MSH process to reduce the curvature. Since you measure the amplitude of the IF at regular intervals, the accuracy increases if you choose $f_{ZF} = f_{sampling}/8$ or $f_{ZF} = f_{sampling}/10$. This is the reason for the 'crooked' value of f_{ZF} in figure 5.

The times between successive zero crossings jump between discrete values (digital noise). For smoothing you should not use a low pass, but rather a quadratic or a cubic polynomial. The iteration has two goals: maximum amplitude and minimum frequency change of f_{ZF}.

The orbital period of the binary system changes extremely slowly and leads to a linear frequency drift. Even the PM of a planet rotating very far out can appear almost straight for years. These two causes can hardly be distinguished if the database covers a period of only twenty years. It is difficult to obtain air pressure data over even longer periods of time.

8 How to search GW?

Three parameters describe a planetary orbit: f_{Orbit}, modulation index a and phase ϕ. The only exception is the PM caused by the Earth's orbit (P=365 days) with the fixed frequency 31.688 nHz. It will not be possible to detect all planets at once using the MSH method because you have to change too many parameters that influence each other.

Previous measurements have all found modulations with at least six different frequencies, which correspond to planets with orbital periods ranging from a few days to around 500 years. That's no guarantee that planets are causing this PM. What other cause could there be? If you are looking for planets with $f_{Orbit} < 10^{-9}$ Hz, you choose a different method than for planets with a small orbit radius. These were described in the previous section.

Knowing the orbit data of a planet from electromagnetic wave observations is very helpful because the amplitude of f_{GW} increases with each planet discovered. The keyword TESS on the Internet provides numerous clues. So far I have discovered a single case in which the MSH method produces a significantly different orbital period than astronomers have calculated from periodic occultations of the binary system.

The search begins with the decision for a binary star system that produces a GW below 120 μHz. This limit follows from the sampling period of the air pressure, according to the theory: $f_{GW} = 2 \cdot f_{orbit}$. It makes little sense to look for a strong spectral line and assign it to a binary star. You don't look for a bunch of spectral lines and put them together using any method. The MSH method looks for the spectral lines that belong together, with the exact frequency spacing and phases being particularly important. Which and how many spectral lines a phase-modulated signal produces is mathematically precisely defined and described in Wikipedia. AM produces different phase relationships that the MSH method can distinguish. Each line that MSH takes into account contributes to the overall information, which is why intermediate results may change noticeably with each newly discovered planet.

You determine by trial and error which modulation frequencies are contained in the broadband spectrum in the bottom right of figure 3. If you manage to undo all modulations, you will end up with a 'clean' spectrum like in the image 3 at the top left. This concludes the detection of this GW and all planets have been found. The entire measurement process consists of several runs, each lasting about 15 minutes. In each run, you determine the data of a maximum of two planets whose orbital periods differ significantly – for example, one planet with $P \approx 1$ years and a second one with $P \approx 50$ years. You start with a modulation index of 0.1, the phase is irrelevant. MSH corrects these values iteratively. The initial frequencies can be chosen as desired; the estimates do not have to be particularly precise because the MSH method has a wide pull-in range. Then you start the iteration and check after about 300 iterations whether the results have stabilized. In particular, if the modulation frequency moves without a recognizable system, choose a different value and restart.

You get a good indication of whether you have discovered a planet if, at the end of an iteration run, you add up how much the actual period lengths of f_{ZF} deviate from the mean (see 'frequency counter' in section 7) . After compensating for all PM, f_{ZF} no longer changes and the sum should be zero. Rounding errors ensure that this value is not achieved.

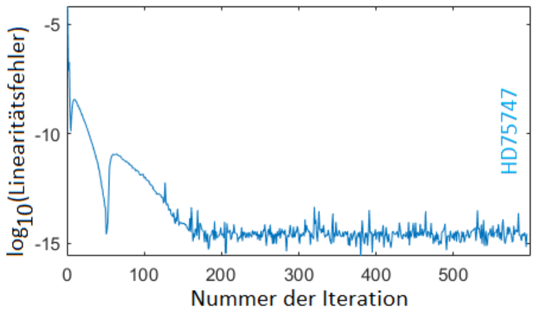

Figure 7): *Example of the convergence of the MSH method. After a few hundred iterations, the frequency variations of f_{ZF} reach the minimum that the CPU can represent (double precision works with 15 valid digits).*

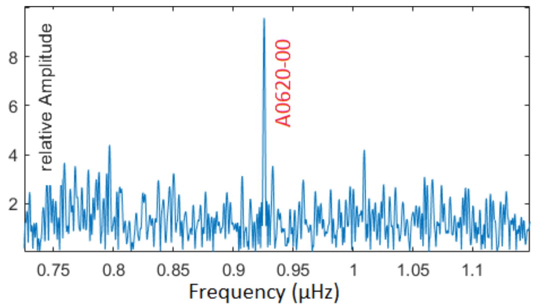

Figure 8): *Broadband spectrum of f_{ZF} after data from all planets were measured. The PM are eliminated, the total energy of the GW is concentrated in one line. The surroundings show distorted spectra of other GW.*

9 Technical hints

It's strange to research GW and planets and distant binary stars at your desk and without looking outside. You have to collect data over a period of many oscillations and because of the very long oscillation period, this takes many years. The DWD data source is compiled carelessly and it takes some time to find and eliminate the numerous errors. There are also other sources: All gravimeters measure the air pressure every minute, so higher frequencies can be analyzed.

You have to write all programs yourself and be able to decipher the purpose of a certain command line even months later. It helps to add lots of comments and describe why you solved the task this way and not another way. Previous versions should be kept in chronological order because sometimes they contain good ideas that you have lost sight of. It used to be a point of honor to do everything yourself. I now think this is a waste of time and am building on MATLAB. Advantage: Very error-free because a lot of people work with it. And fast because it is partly written in assembler. There are younger, free competitors like Python or Octave that are not as mature and are probably slower. It is important to have an extensive library of help programs and good examples. There is also a description of how the prepared programs work internally, because too often proven mathematics – for example the time-consuming convolution of two data series – is cleverly bypassed using FFT in order to save computing time. This does not always promote the quality of the data.

Everything runs alternately on two laptops, so I can try something new or write on one while the other runs at full speed. As a minimum standard I recommend: 500 GB of main memory and 32 GB of RAM. 16 GB is not enough because my MATLAB (R2021b) has problems recognizing and deleting unnecessary files, so after several hours it starts swapping data blocks and is therefore getting slower and slower. No meaningful work is possible with only 4 GB of RAM. The CPU must be at least CORE I5 and work at 2.5 GHz.

If you want to actively search for GW yourself, you can get all the necessary programs and data from me. That's what they're there for.

References

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