6CCP3131 Third year Project in Physics
Acoustic interferometer to mimic LIGO experiment
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ABSTRACT

This project looks into recreating a small scale mimic of the LIGO experiment. An optical Michelson interferometer is used to detect the perturbation caused by monochromatic and non-monochromatic sound waves, deriving from various sources; this is analogous to the gravitational waves radiated from binary star systems or exploding supernovae. The apparatus has successfully detected waves with frequencies up to 2020Hz, whereas the noise inherent in the setup does not allow for frequencies below 50Hz to be picked up. Limitations in resolving power are dependent on the magnitude of the folding frequency used when recording the data. An Arduino is preferable to an oscilloscope when analysing sound waves as it allows for a much larger range of folding frequencies, minimising the error associated with the reading.

When the Arduino works to its theoretical maximum capability, it would take roughly 107 days to correctly identify a frequency of $10^{-5}$Hz with a 1% degree of uncertainty, (calculation time not included). To identify frequency peaks the FFT algorithm has been used.

Through showing that the interferometer setup can detect waves with frequencies between 50Hz and 2020Hz, the experiment can be considered as a success, but for lower frequency waves, the noise inherent in the setup must be accounted for, whereas for higher frequencies, a more sensitive detector should be used.
INTRODUCTION

(1.0) Aim
The aim of the project is to create an optical interferometer which can detect the acoustic analogue of a supernova explosion. The fingerprint of an acoustic wave propagating from a diapason will be measured. A Michelson Morley interferometer will be used, whereby analysis of the interference pattern will allow for the calculation of the frequency of the diapason.

(1.1) Gravitational Waves
When a violent event occurs in space, gravitational waves of a certain frequency are emitted, the frequency follows the formula below:

\[ f \approx \sqrt{\frac{GM}{R^3}} \]  

Where \( G \) is the gravitational constant, \( M \) is the mass of the object emitting the radiation and \( R \) is its radius. The typical magnitude for the frequency of a supernova would be in the kHz range.

Gravitational waves are not part of the Electromagnetic (EM) spectrum and thus add information to that retrieved when analysing EM waves, they also allow the recovery of information which would not be able to leave the event; if light gets trapped due to the large compactness of an object then it becomes impossible to study the event by means of EM waves, however, this compactness leads to a distortion of space-time allowing gravitational waves to be emitted and studied.

When objects perturb the medium in which they are travelling, ripples in the medium’s fabric are generated and propagate away from the centre of disturbance. These ripples manifest themselves on the space-time membrane in the form of gravitational waves. These waves are emitted by accelerating masses much the same way as electromagnetic waves are emitted by accelerating charges.

The existence of such waves was predicted by Einstein in 1916 in his general theory of relativity. With the development of technology in the 90s the detection of such waves became a possibility and is currently an active field of research with international cooperation in the LIGO and eLISA experiments. Gravitational waves have not been directly detected yet, but their effect on a binary pulsar system has been accurately measured and agrees with prediction. The 1993 Nobel Prize for Physics was awarded to Joseph Taylor and Russel Hulse for discovering just such a binary pulsar. The difficulty remains detection; LIGO is composed of four kilometre long arms, and the collision of a nearby neutron star would alter the length of such an arm by less than the diameter of a proton making them extremely hard to detect. LIGO’s successor, eLISA will be much more sensitive, being a space-based version of LIGO, its arms would be five million kilometres long and allow much easier detection of signals.

(1.2) Proceeding
When the tuning fork is hit, a sound wave will propagate through the air. This will cause compressions and expansions in the air, resulting in higher and lower density regions respectively. The density of particles is proportional to the refractive index, hence when shining a laser beam through this perturbed region, it will be affected by these fluctuations in refractive index. By looking at how such fluctuations affect the interference pattern produced on a screen one can extract important information such as the frequency of the sound wave.

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9 Such a monochromatic source is representative of gravitational waves emanating more from fast rotating neutron stars than supernova explosions, in which the frequency spectrum is more complex.
**DESIGN**

**(2.0) Optics**

A Michelson-Morley interferometer was mounted, the diagram below shows a 3D rendering made with Bryce showing the setup:

![Diagram of a Michelson-Morley interferometer](image)

Figure (1) - Setup of the Apparatus; the breadboard allowed the clamping of individual components.

In a **Michelson interferometer**, light from a monochromatic source (S) is divided by a beam splitter (BS), oriented at an angle of 45° to the beam, producing two beams of equal intensity. The transmitted beam (T) travels to mirror M2 where it is reflected back to BS. 50% of the returning beam is then deflected by 90° at the beam splitter and is made to strike the detector (D). The reflected beam travels to mirror M1, where it is reflected. Again, 50% of the beam passes straight through the BS and reaches the detector.

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*b* If the beamsplitter is a 50:50 beamsplitter, other kinds exist giving different intensity ratios for the transmitted beams.
(2.1) Apparatus

The Laser is a He-Ne laser, having a polarized wavelength of 633nm (red). The wave is coherent and monochromatic; since the beam is coherent, light from other sources will not interfere with the interference pattern.

Mirrors provide a way for the beam to change its direction of travel, if M1 and M2 are misaligned, the recombination of the beams occurs at a different location in the BS, resulting in the formation of two signals on D which do not form an interference pattern.

When working with laser light, a cube beamsplitter (CB) possesses the best combination of optical performance and power handling. CBs avoid displacing the beam by being perpendicular to the incident beam. To achieve the best possible performance, CBs should be operated with collimated light as convergent or divergent beams will contribute unwanted spherical aberrations to the setup.

Figure (2) The presence of antireflection coatings on the entry and exit faces of the cube minimize losses inherent in the system and reduces second order reflections. The beamsplitter used split the beam into two beams of equal intensities.

To collimate the beam, a telescopic lens arrangement was used. The divergence of the beam without collimation was measured as $9.3 \pm 0.2 \times 10^{-3}$ radians. With the two lenses in place (L1 being converging and L2 diverging), the beam was collimated and the divergence was decreased by a factor of 67% to $3.2 \pm 0.2 \times 10^{-3}$ radians. The telescopic arrangement consists in making the beam behave as though it came from infinity and is achieved in the following configuration:

Figure (3) The resulting ray appears to come from infinitely far away, removing the divergence inherent in the laser. The two lenses were 100mm apart, as the focal lengths of each lens were: 140mm (converging) and 40mm (diverging).
The orientation of the planoconvex lens is important as even though a flipped lens would have achieved convergence, it would have done so at the expense of creating spherical aberrations. The spread is larger when the planar side is facing the incoming radiation.

A piezoelectric was connected to a signal generator and attached to M2. This acted as a test for the apparatus and allowed the mirror to oscillate at various frequencies. The distance travelled by M2 due to excitation of the piezoelectric was a secondary investigation inherent in the project.

The detector used allowed the intensity of light hitting it to be recorded. When two or more waves interact with one another an interference pattern is produced. This pattern is a result of the phase difference between the waves. When the waves are in phase constructive interference occurs and the resulting amplitude of the two superimposed waves is a maximum, on a screen, this is seen as a light fringe. When the waves are \( \pi \) out of phase, destructive interference occurs and the resulting amplitude is 0, on a screen this is seen as a dark fringe.

If a large detector is used, many interference fringes will be detected, leading to a less pronounced signal due to the multiple combinations of different constructive and destructive interference fringes. If on the other hand a small detector is used, the central maxima will saturate the detector area and lead to a more pronounced change when moving from fringe to fringe. Using a small detector does have its drawbacks as less light is captured, and there is less room for error in the positioning of the central maxima, therefore a balance was found between ease of use, voltage recorded and detector saturation. The detector used was a square detector 1mm x 1mm.

A sinusoidal signal was detected, corresponding to the variations in intensity in the central maxima (converted to a voltage) over frequency. When a dark fringe was recorded the signal was at a trough, when a light fringe was recorded the signal was at a peak. An electronic board was used to alter the output signal coming from the detector so as to best visualise it on an oscilloscope, this allowed changing the gain\(^d\) and offset\(^e\) of the signal coming from the detector.

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\(^c\) Image freely taken from: folk.uio.no/walmann/Publications/Master/node8.html
\(^d\) Measure of the ability of an amplifier to increase the amplitude of a signal from the input to the output port
\(^e\) Parameter which defines the DC voltage required to make the output zero in an amplifier
DATA ANALYSIS

(3.0) Acquisition of data using an oscilloscope
The oscilloscope was able to acquire data at a very high frequency; the maximum sampling rate being 2GS/s (2 Giga Samples per second). The piezoelectric was made to oscillate via the signal generator:

Figure(6) Snapshot taken with the OpenChoice Desktop software. The two signals are modulated at an operating frequency of 2.31kHz.

The oscilloscope used in this experiment took a maximum of 2500 data points before running out of RAM, this will be of importance when performing the FFT analysis.

(3.1) Fast Fourier Transform (FFT)
From the set of coordinates, the dominant frequency of the signal had to be calculated, this was done by carrying out a FFT. The FFT allows the deconstruction of a signal into its sinusoidal components and detects the component with the highest amplitude. The Fourier Transform of the signal recorded should show a peak equivalent to the frequency at which the piezoelectric was vibrating at (around 2.31kHz). So as to be able to plot the Fourier transform data properly, the FFT amplitude has to be plotted against the FFT frequency.

(3.2) FFT frequency & FFT Amplitude
The folding frequency¹ is the step for which the FFT components are calculated. According to the Nyquist theorem of sampling; the maximum frequency component that can be determined using a given dataset of points equally spaced t seconds apart is equal to 1/(2t). The folding frequency is therefore:

\[
\text{Folding frequency} = \frac{1}{\text{Number of data points}\times\text{Sampling Interval}}
\]  

(2)

Where the number of data points used was 2500; once the folding frequency had been found, the FFT normalised amplitude was calculated:

\[
\text{Folding amplitude} = \frac{2\times\text{FFT output}}{\text{Number of data points}}
\]  

(3)

¹Term used interchangeably with Nyquist frequency
²The division by the number of data points allows for the normalisation of the amplitude, the factor of two comes into play as the FFT is a two-sided power spectrum displaying half the energy at the positive frequency and half the energy at the negative frequency; to convert a two-sided spectrum to a single-sided spectrum, the second half of the array is discarded and every point is multiplied by two.
By changing the time resolution dial on the oscilloscope, the sampling rate could be increased or decreased; this was fundamental in getting the best possible resolution when looking at a particular wave. The optimal resolution is achieved when there is only one wave on the oscilloscope screen, as higher than this value would increase the folding frequency, lowering the resolution. Lower than this, there is not enough information to successfully recreate a faithful representation of the wave.

Figure 7 – The reading from the graph shows a value of 2kHz, differing from the 2.31kHz used (figure 6). The difference between these two results is: ±13.42%. Top right is the waveform seen on the oscilloscope. The dashed red line shows the frequency under investigation, the green dashed line shows the first overtone. The folding frequency used was of 400Hz.

(3.3) Divergence

A 13.42% error is very large, however, it is only so for the frequency under investigation. Had a frequency of 2000Hz been investigated, there would have been an error of 0%. The error is dependent on the frequency of the signal generator and the folding frequency used, as well as the number of data points gathered, which in the case of using the oscilloscope, remains constant.

If the frequency under investigation was to be 200Hz, it would possess an unacceptable 100% error, as the sole frequencies allowed by the folding frequency periodicity are 0 and 400Hz. To decrease the error, a smaller folding frequency has to be used, thus the sampling rate needs to be decreased.

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b Five waves were shown on the screen because the time dial on the oscilloscope allowed only for discrete changes; a lower sampling rate would have made less than one wave appear on the screen, this will be of importance further on when comparing the usefulness of the Oscilloscope to an Arduino Due
(3.4) Implications of sample size

A sample size that is a power of two will be Fourier\textsuperscript{13} transformed the fastest, and is almost the same speed for sample sizes which possess small prime numbers as factors, however, when dealing with very large sample sizes not falling into the aforementioned categories, especially so if these sample sizes happen to be prime numbers, the computation time becomes non-negligible. From this point onwards in the experiment, a sample size of 2048 points (\(2^{11}\)) will be used, so as to remain faithful to the idea of a fast computation.\textsuperscript{1}

(3.5) Decreasing the sampling rate

The signal generator was switched off and a 440Hz tuning fork was used. The sampling interval in the graph below was 0.0001s; this allowed the folding frequency to decrease to 4.88Hz, roughly 83 times better resolution than what had been previously used with the signal generator.

Figure (8) - The peak frequency is found as being equal to 439.45Hz, the next possible peak would have been 444.34Hz. The margin of error when using a sampling interval of 0.0001s was ±1.1%. Data points after a FFT frequency of 1500Hz have been omitted, as there were no characteristic peaks.

The real uncertainty is actually lower; when performing the FFT, the true frequency value lies between two extremes, if the value is closest to one of the two extremes, it will be attributed to that specific value, and hence, the maximum uncertainty occurs when the true frequency lies exactly between the two extremes. In the case of a folding frequency equal to 4.88Hz, this leads to a percentage error of 0.6% when using a sample interval of 0.0001s for detection of a 440Hz wave, which is a very good uncertainty. From figure 8, a second distinct peak can be seen at a frequency of 878.91Hz, this is a harmonic overtone, with frequency double that of the first peak, and is a consequence of the diapason vibrating at a series of distinct normal modes of vibration, all multiples of the main tone (440Hz). This will be of importance when investigating the relative FFT amplitudes of the FFT frequencies for a signal possessing multiple frequencies as an overtone can add to the FFT amplitude of a wave under investigation.

\textsuperscript{1} Especially more so when in section 4.5 the number of data points can potentially be increased to very high values when using an Arduino; sample sizes which are powers of two will become convenient.

\textsuperscript{1} Now the number of data point used is 2048, hence, the folding frequency is 4.88Hz, following from formula 1
(3.6) Noise FFT
So as to understand how much of an impediment noise was to the experiment, it was measured separately, this allowed understanding whether there was any peak frequency due to noise around the frequency at which the diapason vibrates.

![FFT of noise in room](image)

Figure (9) - There are no particular peaks around the 400Hz mark, hence if a peak is detected it will be a faithful representation of the frequency of the diapason. The Folding frequency used was 12Hz. However, noise does not become negligible when looking at low frequencies. Data recorded beyond 1200Hz showed no peaks, and for the purpose of clarity was not included.

The room in which the experiment was undertaken had a very loud air conditioning system, the FFT of the noise was taken in the eventuality that the experiment was to be carried out when it was on, however, there were no particular peaks visible when performing the FFT of such a system, and the general shape was very similar to that in figure 9. What seems to be a relatively high peak at 232Hz is in reality a one off event, as such a peak was not present in the noise FFT spectrum when the air conditioning was turned on. There are pronounced low frequency peaks between 0 and 50Hz, making the correct detection of low frequency waves nigh impossible, limiting the use of the apparatus as a tool to measure gravitational waves. In comparison, the LIGO experiment is not capable of detecting waves with frequencies below 1Hz.\(^\text{14}\)

It could be possible to subtract the FFT amplitude of the noise graph from that of the graph under investigation, removing the sharp peaks found at low frequencies which make the graph ‘squashed’ by the initial noise in the 0-50Hz range, however, this subtraction is feasible only if the folding frequency of the two graphs match, and this is not the case in the vast majority of cases. To get round this problem, the data can be plotted with the 0-50Hz range removed, as this contributed the most to the illegibility of the graph by compressing it, this will be done for later graphs.
EXTENSION

(4.0) Multiple frequencies
Waves possessing multiple frequencies were generated with the use of a laptop computer. It was made sure that none of the frequencies analysed were multiples of each other, as the contribution of harmonic overtones would have led to misleading results. The frequencies were all played at the same volume, so as to not privilege one signal over another.

(4.1) Upper limit of frequency detected
The graph below shows the FFT plot for the following frequencies: 2kHz, 2.5kHz, 3kHz and 7kHz, when using a laptop computer and all with the same amplitude, the folding frequency was 122.07Hz, this allowed for a maximum margin of error of ±3.1% corresponding to 2kHz, precise enough to resolve the frequencies. The noise in the initial part of the spectrum (0Hz-600Hz) has been removed, to reduce the incidence of noise on the clarity of the graph.

![FFT Graph](image)

Figure (10) - As can be seen there is a noticeable peak corresponding to 2000Hz but the peaks at 2500Hz, 3000Hz and 7000Hz are barely detectable amidst the noise. A characteristic peak at 1953.13Hz can be seen. The folding frequency was 122.07Hz. Top right, the waveform corresponding to this perturbation.

Removing the initial noise-affected frequency is not enough to resolve the peaks to a satisfactory standard and subtraction of the noise all along the spectrum is compulsory. However, had a FFT of the noise in the room been carried out at a folding frequency of 122.07Hz, the spectrum would be time and position specific, hence would still not be valid if a subtraction was to be performed.

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In this experiment, it was assumed that the amplitude of different frequency waves was the same, although it is not in reality.
It is interesting to understand why there is such a large incidence of noise in figure 10, when using the laptop computer, whereas in figure 8, when using the diapason, there is a crisp peak at 440Hz and even the second harmonic is clearly noticeable at 880Hz, with the noise signal being dwarfed by a distinct FFT peak. When using the signal generator, there is a very crisp peak at 2000Hz, but when looking at figure 10, this is not the case. It can be concluded that in terms of quality of disturbance, the diapason ranks first, followed by the signal generator and by the laptop computer, responsible for the most noise, probably due to the inefficiency of the speakers. From this, the idea of subtracting the noise spectrum from the other graphs, even when possessing matching folding frequencies, is further proven to be invalid, as the noise is dependent on the source causing the disturbance.

More frequencies were investigated to test the validity of figure 10, in the plot below, the following frequencies were created with the laptop computer: 120Hz, 170Hz, 650Hz, 1200Hz, 2000Hz, 7000Hz and 11000Hz, to locate peaks at high frequencies better, the y axis was made to scale logarithmically.

Figure 11 – Characteristic peaks can be seen at frequencies of 646.97Hz, 1196.29Hz and 2001.95Hz, corresponding to: 650Hz, 1200Hz, 2000Hz, all other peaks are not distinguishable from the noise, confirming the large peak seen in figure 10, followed by indistinguishable peaks at 2500Hz and 7000Hz. The folding frequency used was 12.21Hz. A logarithmic scale allowed for better identification of peaks amongst noise.
(4.2) Resolving power

It was interesting to investigate whether the folding frequency value was the sole limitation in resolving two similar frequencies (ie within 1-2% of each other). To test this, two sets of frequencies were used: 650Hz and 680Hz and 2000Hz and 2020Hz. These frequencies were used because they showed high peaks among the noise and are sufficiently separated to account for a possible difference in the resolving power of the apparatus dependent on the frequency under investigation. In both graphs the folding frequency used was 2.4Hz.

![FFT for signals of frequency 650Hz and 680Hz. As can be seen the two frequencies can be clearly resolved.](image1)

![FFT for the signals of frequency 2000Hz and 2020Hz. The two peaks can be clearly resolved as well.](image2)

From figures 12 and 13 it is clear that waves having frequencies within 2-3% of each other can be resolved. In further investigation, the difference between the two waves under analysis was further reduced and the waves were resolvable up until when the difference between the waves was the same as the folding frequency used. It can be concluded that the only impediment to resolving waves is the folding frequency used, when looking at frequencies not greatly affected by noise.

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1 The data for such a reading is not available as a different oscilloscope was used which could not transfer data.
(4.3) Analysis of folding frequency and resolving power of the instrument
The graph below shows which folding frequency should be used for specific frequencies. If the setup was to be used to investigate perturbations of 100Hz a folding frequency of 2.4Hz would be preferred to one of 4.8Hz, leading to a lower % error, (2.31% as opposed to 4.76%).

Figure 14–It can be seen how the % error when detecting the frequency is maximal when the frequency is close to the folding frequency and minimal when the frequency is farthest from the folding frequency. Also, the range of frequencies which can be analysed is shown; for example a folding frequency of 2.4Hz can be used for frequencies ranging between 2.4Hz and 4915.2Hz, as the maximum number of data points used for the FFT is 2048. The same argument applies for the other folding frequencies. Other folding frequencies were available but it was decided to graph just those found in previous parts of the experiment.
(4.4) Arduino
Up until this stage, the oscilloscope has been used as the sole means of data collection and as such, the folding frequency was inversely proportional to the value of the sampling interval, as the number of data points remains constant. However, if a different device, such as an Arduino is used, the number of data points gathered can be increased indefinitely. An Arduino allows the plotting of many more curves in figure 14, as it allows the folding frequency to adopt a large number of different values. It therefore is a much better resolving tool than the oscilloscope as it is not limited to the large discrete nature of the dial on the oscilloscope. The folding frequency would therefore always be chosen in a way to minimise the % error linked to a particular frequency under investigation.

In the final stages of the project, an Arduino Due was used, set to a sampling interval of 461µs, (sampling frequency of 2170Hz, roughly the same magnitude as what is possible with an oscilloscope) and the number of data points gathered was chosen to be 17500. This allowed for a folding frequency of the order of 0.12Hz, which is roughly 20x better resolution than the best resolution used with the oscilloscope (2.4Hz). The maximum frequency detectable using these settings was 2100Hz, hence, it would have been possible to detect the upper frequency limitations of the apparatus and all the waveforms calculated previously with 20x better resolution.

(4.5) Pushing to the limits
The hardware limitations in using an Arduino are of importance. When using the Arduino Due, the analogue to digital clock rate is 21MHz, corresponding to a minimum theoretical sample interval of 37.6ns. The maximum number of data points gathered becomes dependent upon the measuring time:

\[ Time \text{ of measurement} = \text{Max number of data points gathered} \times \text{Sampling interval} \]

This can be further simplified by using equation 2 to:

\[ Time \text{ of measurement} = \frac{1}{\text{Folding frequency}} \]

If gravitational waves of frequency \(10^{-5}\)Hz were to be investigated (very low end of the spectrum of frequencies), assuming a folding frequency of \(10^{-7}\)Hz (1% uncertainty) and assuming a sample interval of 37.6ns; from formula 2 a total of \(2.66\times10^{14}\) data points would be required. Using equation 3/4 this is achievable in \(10^{7}\)s, or roughly 116 days. Assuming that the only limitations lie in the clock rate. On the other hand, when looking at supernovae (frequency: 1kHz and hence folding frequency 10Hz to achieve 1% error) we have a time of measurement equal to roughly one microsecond, which is exactly the total sample time taken in the experiment.

The use of a sample size equal to \(2^N\) is encouraged as the computational time when performing the FFT would become very long for such large data samples. Hence, to conclude, the best trade-off between calculation speed, data acquisition speed and % error linked with waves of \(10^{-5}\)Hz can be calculated. It comes out that the closest value of \(2^N\) to \(2.66\times10^{14}\) is when: \(N=48\), giving a maximum number of data points equal to: \(2.81\times10^{14}\). The Folding frequency when using this number of data points and a maximal sample interval of 37.6ns is: \(0.95\times10^{-7}\)Hz. This results in a lower % uncertainty, to the expense of a longer sampling time of: 122 days, but will lead to a lower calculation time when performing the FFT of the data.

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\(a\) To clarify: dial which changes the sample interval while maintaining the number of data points constant, whereas the Arduino allows a very high resolution of data points to be gathered, while keeping the sample interval constant

\(b\) Interesting to point out how the oscilloscope has a minimum sample interval of 50ns.

\(c\) Corresponding to: 3.325x10^{13} bytes or: 33TB of data.
(5.0) Conclusion

The apparatus is capable of successfully detecting frequencies between 50Hz and 2020Hz; these values are valid when using a laptop computer as a supernova, if a collection of different frequency high quality sound wave sources are used (such as diapasons) it may be possible to push the frequency extremes farther. This range of frequencies account for a small part of the gravitational wave spectrum, however, LIGO itself has difficulty in measuring waves below 1Hz; it is known that seismic effects occur at around 60Hz\(^1\), hence, the setup picks these vibrations up as noise. The apparatus is most suitable for detection of supernovae with relatively low mass or relatively high radius.

When using the diapason, the frequency detected was 439.45Hz±0.6%, which is an excellent uncertainty. This was made possible by using a folding frequency of 4.88Hz, achievable by using a sampling rate of 0.0001s. The sound wave generated by the diapason was so 'clean' that even a second overtone was clearly detectable among the noise. This monochromatic spectrum however is a characteristic more eminent in a rotating binary star system, than in a supernova, which emits many different frequencies. Hence the investigation carried out with a diapason matches more with the nature of a rotating system of binary stars, whereas that carried out with the multiple waves from the PC matches most with the supernova explosion.

After proving that the resolution of the apparatus is dependent mostly upon the folding frequency (figures 12, 13) the most appropriate folding frequency for a specific perturbation frequency can be chosen (from figure 14). For example, when looking at a perturbation frequency of 1000Hz, there is the option to use a folding frequency of 2.4Hz, 4.8Hz, 244Hz and 488Hz with the oscilloscope; % errors respectively being: 0.24%, 0.48%, 25.22% and 49.3% respectively; the folding frequency to be used should be 2.4Hz.

It was concluded that the noise has to be measured simultaneously with the signal so as to be representative of the conditions under which the experiment was undertaken. However, repetition of the measurements could also allow subtraction of an average noise spectrum from the spectrum of the frequency under investigation.

When using an Arduino Due, the resolution is much increased due to the large number of data points which can be gathered, something impossible with the oscilloscope. When at roughly the same sampling interval, the Arduino outperforms the oscilloscope with 20x superior resolution. Hence, when looking at supernova-like perturbations (non-monochromatic), the Arduino should be used as it allows a much better resolution of a multiple peaked spectrum.

The apparatus cannot detect waves beyond 2020Hz, which is a problem when looking at large mass and low radii supernovae exploding, this could be due to the following reasons, limitations in the detector’s capability to detect such rapidly changing variations in intensity, or a more physical based explanation resides in the energy loss of the wave to the medium through which it travels; in low frequency waves, the damping factor is lower than in high frequency waves, hence, less energy is transferred to the medium. However, the change in frequency is so abrupt after 2020, that the limitation can be regarded as being due to the detector and not the evanescent properties of waves when travelling through media. Furthermore, air has a very low damping factor, and over one metre the frequencies used should still be detectable.

Improvements to the experiment would include being able to measure the noise for a particular time and configuration, while at the same time taking the reading, this would allow peaks found after 2000Hz and below 50Hz to be seen more clearly. Furthermore, the apparatus could be sent into space, so as to not allow seismic effects to impinge on the readings; as has been proposed with the LISA experiment.
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