Measuring the Speed of Sound Through Doppler Effect

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1 Introduction

The objective of this experiment is to measure the speed of sound using the Doppler Effect. We performed this experiment by using different methods to collect sound from a moving source, compare the measured frequency to the emitted frequency, and determine the speed of sound by using the relationship of the two frequencies, which is given by the Doppler Effect. If successful, we expect to achieve agreement between a calculated theoretical value of the speed of sound and our experimental result.

2 Theory

2.1 What is the Doppler Effect?

Sound travels in waves in the air, outward from the source. When an object emitting sound is traveling relative to the observer, the relative wavelength of the sound changes, which thereby causes a change in the frequency. This is given by the wave speed equation $v = \lambda f$, where v is the wave speed (determined by the medium), λ is the wavelength, and f is the frequency. Given that v remains constant for a certain medium (in this case, air at a certain temperature), if λ decreases f must increase. As the object is traveling towards the observer, the wavelength compresses, which makes the frequency higher. Conversely, when the object is traveling away from the observer, it lengthens the wavelength, thereby lowering the frequency.

2.2 How Can We Measure the Doppler Effect?

We can measure this frequency change by observing a traveling sound source, recording its frequency, then comparing that to the source frequency. The source frequency would be measured, for example, from the stationary sound source. The source frequency, f, and the Doppler shifted frequency, f', are related to each other by the speed of sound, and the velocities of the sound source and observer. The speed of sound is the speed of motion that the wave, as a whole, travels at in a given medium. Note that, for air, the speed of sound is dependant on temperature of the air, and is approximated by the equation $v = \left(331.4\ \frac{\mathrm{m}}{\mathrm{s}}\right) + \left(0.6\ \frac{\mathrm{m}}{\mathrm{s}\ {}^{\circ}\mathrm{C}}\right) T_c$, where v is the speed of sound, and T_c is the temperature of the medium.

2.3 Doppler Effect Mathematics

The Doppler effect can be seen when both or either the source and observer are moving. The general Doppler equation for sound is $f' = f\frac{v \pm v_o}{v \pm v_s}$ where v is the speed of sound, v_o is the observer velocity, and v_s is the source velocity. The plus or minus signs in the numerator and denominator are determined by the path that the source and observer are undergoing relative to each other. For simplicity, we chose the observer to be stationary, and the source to travel directly towards the observer, which was a camera. It is important for the source frequency and the observer to be on the same plane for this equation to be most accurate. Since the emitted sound traveling towards the observer raises the frequency of f, the source velocity was subtracted in the denominator such that the overall fraction, and hence f', would be larger for a positive velocity. With these parameters, our version of the Doppler effect equation becomes $f' = f\frac{v}{v - v_s}$.

2.4 Finding the Speed of Sound from Doppler Effect

With this specific Doppler effect equation, it is possible to experimentally determine the speed of sound, v. One method to isolate the speed of sound from the Doppler equation would be to rearrange the equation to graph it such that the slope is in terms of v. Algebraically manipulating the equation to fit the equation of a line, we get $v_s = v\left(1 - \frac{f}{f'}\right)$. On the graph, we will plot the source velocity, v_s, as a function of $\left(1 - \frac{f}{f'}\right)$. Then, the slope of the best fit line on this graph would be the speed of sound, v. Varying the source velocity while holding the other variables constant allows us to get many different data points, thereby letting us extract an accurate value from the slope on our graph.

2.5 Analyzing the Speed of Sources

If the source was moving in a linear path directly towards the observer, the source velocity can be determined by the velocity equation for linear motion, $v_s = \frac{d}{t}$, where d is the distance traveled and t is time elapsed. Similarly, if the source was moving in a circular path towards the observer, the tangential velocity of the source can be determined by the equation $v_s = \frac{2\pi r}{t}$, where r is the radius of the motion, and t is time elapsed.

3 Procedure

We conducted the experiment in two different ways, varying the type of motion of the sound source.

One group member, Alex, performed the experiment with linear motion as shown in Figure 1 below. He drove a remote-controlled car that carried a speaker at a constant speed for a certain length directly towards and under the recording device. He was able to vary the velocity of the remote-controlled car by changing the distance of acceleration before the car reached constant velocity.

The other group members, Quinn, Eliza, and Audrey, performed the experiment with circular motion, spinning a speaker over their head with a nonelastic string for at least five seconds to reach constant tangential velocity. The setup is shown in Figure 2 below. That tangential velocity was varied by changing the length of the string, which changed the horizontal distance the speaker traveled. The angular velocity remained roughly constant throughout each data run due to spinning at a constant rate.

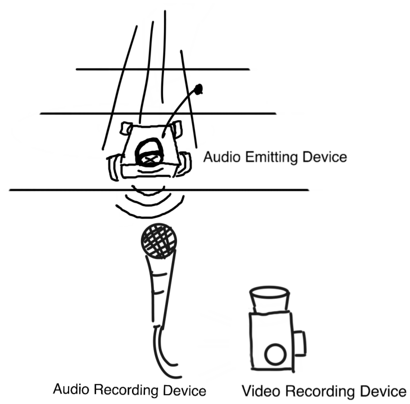

Figure 1: Setup and diagram of linear motion experiment

We all filmed and recorded the sound of the experiments with a camera and microphone. We also used a tape measurement as a reference for video analysis to track the path of the speaker to determine its velocity - the path of the car in the linear motion experiment and the path of the speaker in the circular motion experiment. Throughout all of the experiments, each speaker emitted a constant frequency of 4000 Hz. For an accurate recording, we tried to maintain the same plane between the speaker and recording device.

The experiments were performed outside in areas where there would be little to no disturbance to and from the surroundings. This was to eliminate background noise and to prevent beat frequencies from occurring. There were also safety considerations for ourselves and the surroundings, especially for the

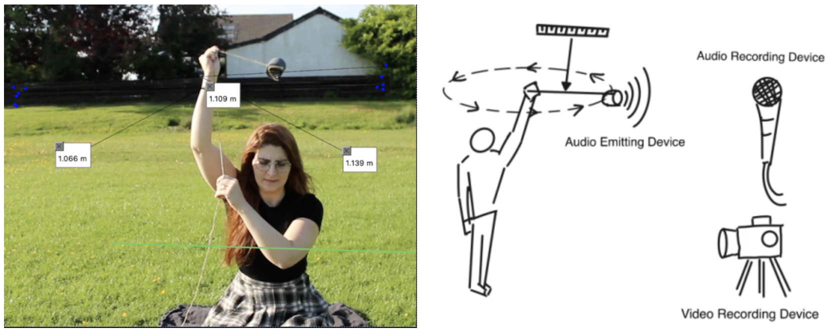

Figure 2: Setup and diagram of circular motion experiment

circular motion of the speaker.

4 Data

This experiment was split into two sections - a preliminary data run and a final data run. In the preliminary data run, we collected audio and video data using only one technique, whereas we made several improvements, as detailed later, and used two different techniques in the final data run. The two sections below show the majority of the data collected and used for analysis from the sections. For the rest of the audio data, please see Appendix 1.

4.1 Preliminary Data Run

Table 1 below shows the temperature data collected for when each experiment was performed. In the table, T represents the temperature.

Temperature Data		
Name	T ($°C$)	δT ($°C$)
Alex	16.0	0.3
Audrey	17.2	0.3
Eliza	12.7	0.5
Quinn	13.3	0.3

Table 1: Temperature data and uncertainty for Preliminary Data Run

4.1.1 Video Analysis

Table 2 below shows the data collected from analyzing the experiment videos in Logger Pro. In the table, r represents the radius of motion, N represents the number of oscillations counted, t represents the amount of time taken to complete those oscillations, and, finally v_s is the source velocity (calculated from the aforementioned columns).

Video Analysis								
Set #	r (m)	δr (m)	N	δN	t (s)	δt (s)	v_s (m/s)	δv_s (m/s)
Alex								
1	0.49	0.05	1.00	0.05	0.300	0.010	5.5	0.6
1	0.44	0.05	1.00	0.05	0.300	0.010	4.9	0.6
1	0.46	0.05	1.00	0.05	0.367	0.010	4.8	0.6
2	0.80	0.05	1.00	0.05	0.300	0.010	6.3	0.5
2	0.83	0.05	1.00	0.05	0.298	0.010	6.9	0.7
2	0.76	0.05	1.00	0.05	0.332	0.010	6.0	0.5
3	1.52	0.05	1.00	0.05	0.934	0.010	6.8	0.5
3	1.40	0.05	1.00	0.05	0.767	0.010	7.5	0.6
3	1.43	0.05	1.00	0.05	0.800	0.010	7.5	0.5
4	1.75	0.05	1.00	0.05	0.500	0.010	8.3	0.5
4	1.72	0.05	1.00	0.05	0.500	0.010	7.9	0.4
4	1.72	0.05	1.00	0.05	0.400	0.010	8.8	0.4
Audrey								
1	0.36	0.05	1.00	0.05	2.8	0.4	5	1
2	0.48	0.05	1.00	0.05	2.1	0.2	8	2
3	0.53	0.05	1.00	0.05	1.9	0.2	9	1
4	0.60	0.05	1.00	0.05	1.7	0.2	10	1
Eliza								
1	0.3	10.05	1.00	0.05	0.50	0.06	4.1	1.4
2	0.56	0.05	1.00	0.05	0.50	0.06	7.0	1.2
3	0.77	0.09	1.00	0.05	0.57	0.06	9.2	2.5
Quinn								
1	1.00	0.03	1.00	0.05	0.99	0.05	6.34	0.80
2	0.75	0.03	1.00	0.05	0.85	0.05	5.54	0.77
3	0.50	0.03	1.00	0.05	0.72	0.05	4.36	0.76

Table 2: Data from video analysis for preliminary data run

4.1.2 Audio Analysis

Table 3 below contains the results from analyzing the spectrogram from the audio recordings along with each data run. In the table, f' represents the measured Doppler shifted frequency.

Audio Analysis		
Set #	f' (Hz)	$\delta f'$ (Hz)
Alex		
1	4510	50
2	4460	50
3	4210	50
Audrey		
1	4070	40
2	4090	40
3	4080	40
4	4090	40
Eliza		
1	4500	130
2	4500	130
3	4600	120
Quinn		
1	4500	700
2	4600	700
3	4600	700

Table 3: Data from audio analysis

4.2 Final Data Run

Table 4 below shows the temperature data. T represents the temperature. See Appendix 1 for the full audio raw data.

Temperature Data		
Name	T ($°C$)	δT ($°C$)
Alex	20.0	0.3
Audrey	20.0	0.5
Eliza	23.0	0.5
Quinn	18.9	0.5

Table 4: Temperature data and uncertainty for Final Data Run

4.2.1 Video Analysis

Tables 5 and 6 below contain data collected from analyzing the experiment videos in Logger Pro. The first table contains data from the linear motion experiment performed by Alex, whereas the second table contains data from the circular motion experiment performed by Audrey, Eliza, and Quinn. For the linear motion data table, d represents linear distance, t represents time elapsed and v_s represents linear velocity (calculated from the aforementioned columns). As in the Preliminary Data Run, for the circular motion data table, r represents the radius of motion, N represents the number of oscillations counted, t represents the amount of time taken to complete those oscillations, and, finally v_s is the source velocity (calculated from the aforementioned columns).

Linear Motion: Video Analysis						
Set #	d (m)	δd (m)	t (s)	δt (s)	v_s (m/s)	δv_s (m/s)
1	1.52	0.08	0.367	0.008	4.2	0.3
2	1.52	0.08	0.251	0.008	6.1	0.5
3	1.52	0.08	0.217	0.008	7.0	0.6
4	1.52	0.08	0.200	0.008	7.6	0.7

Table 5: Linear motion (Alex's data) video analysis

Circular Motion: Video Analysis								
Set #	r (m)	δr (m)	N	δN	t (s)	δt (s)	v_s (m/s)	δv_s (m/s)
Audrey								
1	0.331	0.005	1.00	0.05	0.314	0.005	6.6	0.2
2	0.553	0.005	1.00	0.05	0.345	0.005	10.1	0.2
3	0.801	0.005	1.00	0.05	0.372	0.005	13.5	0.3
4	1.048	0.005	1.00	0.05	0.412	0.005	16.0	0.3
Eliza								
1	0.33	0.04	1.00	0.01	0.441	0.005	4.7	0.7
2	0.55	0.04	1.00	0.01	0.562	0.005	6.1	0.6
3	0.79	0.05	1.00	0.01	0.603	0.005	8.2	0.7
4	1.17	0.06	1.00	0.01	0.638	0.005	11.5	0.8
Quinn								
1	0.60	0.01	1.00	0.01	0.76	0.02	5.0	0.2
2	0.88	0.01	1.00	0.01	0.77	0.02	7.2	0.3
3	1.12	0.01	1.00	0.01	0.80	0.02	8.8	0.3

Table 6: Circular motion (Audrey, Eliza and Quinn's data) video analysis

4.2.2 Audio Analysis

As in the Preliminary Data Run, Table 7 below contains the results from analyzing the spectrograms from the audio recordings along with each data run. In the table, f represents the measured source frequency and f' represents the Doppler shifted frequency.

Audio Analysis				
Set #	f (Hz)	δf (Hz)	f' (Hz)	$\delta f'$ (Hz)
Alex				
1	4000	2	4050	30
2	4000	2	4060	30
3	4000	2	4060	30
4	4000	2	4070	30
Audrey				
1	4017	2	4070	40
2	4015	2	4140	40
3	4016	2	4170	40
4	4018	2	4260	40
Eliza				
1	3986	2	4060	30
2	3986	2	4070	40
3	3986	2	4100	30
4	3986	2	4130	30
Quinn				
1	3996	2	4070	70
2	3996	2	4070	70
3	3996	2	4030	70

Table 7: Data from audio analysis

4.3 Uncertainty

For our specific raw uncertainties, each experiment had different sources of uncertainty. The linear, radio-controlled car experiment, for example, had the following sources of uncertainty. According to Alex, it was difficult to see where the car started and ended. Thus, the distance might have been off. Also, it was unclear when the car passed over each line. Alex also cited his ability to see where the waveforms began and ended when interpolating between the audio samples as sources of uncertainty. The circular motion experiment had different sources of uncertainty. Those sources of uncertainty included measuring the radius of rotation and measuring the period of one revolution in Logger Pro. Each experiment had uncertainty in the accuracy of the frequency recorded through Audacity and the local temperature measurement. The uncertainties for each individual measurement are recorded along with the raw data in all of the tables above, and in the extended raw data in Appendix 1.

5 Analysis

Our analysis will be primarily be split into two sections, the preliminary data run and the final data run. Our analysis relied heavily on Logger Pro, a program similar to Excel that has a strong graphing utility, and Audacity, a program designed to analyze audio files. Our preliminary data run had significantly more errors and greater uncertainty than the final data run. We improved various parts of our experiment and analysis in the final data run, which led to a more reliable product.

5.1 Preliminary Data Run Analysis

Our preliminary data run could be improved, as demonstrated from Figure 3, which is a graph of our first data run results.

5.1.1 Results

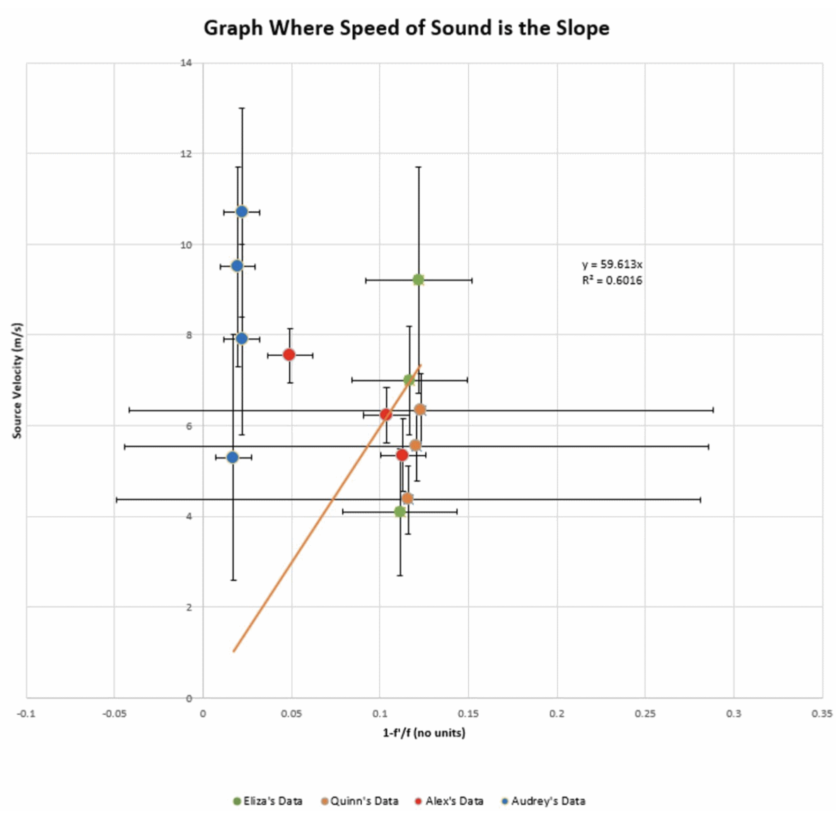

Figure 3: Results graph for preliminary data run

There are several reasons why our initial results were so varied. Some of the main reasons include: different methods of data collection between group members and inconsistent methods of analysis amongst the group. The primary inconsistencies amongst the group for data collection and analysis were: having no uniform method of analysis of the waveform graphs; not having a standard to measure period of one revolution of the string; poor data collection methods; and problems measuring the time on the waveform graph.

These errors may seem trivial. However, in aggregate, they posed serious challenges to our results, as is evidenced in Figure 3, the graph for our first data run, and led to an unreliable and unworkable speed of sound result. The uncertainty was too great and the data points were too varied to find an uncertainty value for our initial speed of sound. In other words, we knew our first data run was riddled with errors and we would have to revamp our whole process in order to get reliable results in final data run.

Before discussing the final data run, it is important to focus in on the four errors that were previously mentioned to understand why they led to unreliable results and to understand why we had to burnish our experiment by changing those aspects.

5.1.2 Errors in Analyzing Waveforms

The first problem was having no uniform method of analyzing the waveforms. This was problematic because, in the process of doing the first analysis, our group was not synchronized; we were all doing something slightly different. For example, some group members measured 10 waveforms, others 100. Do we measure from peak to peak? Do we include the first peak? These were confounding questions that led to additional error and inconsistencies in our results.

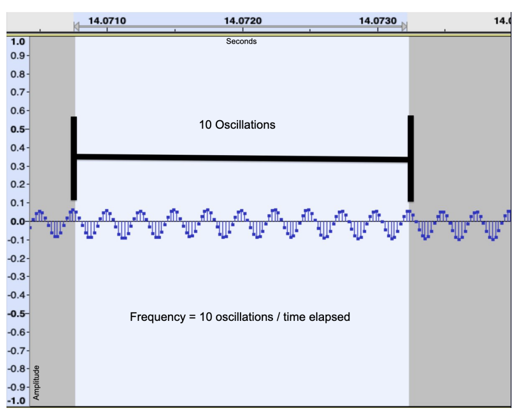

Figure 4: Example of waveform analysis for a data point. The vertical axis shows loudness, whereas the horizontal axis shows time in seconds

Secondly, we had problems measuring time on Audacity for the waveform analysis. As shown in the waveform analysis example in Figure 4, there are tic-marks on the upper horizontal scale in Audacity. In this image, the photo is not zoomed-in to the fullest extent. It is possible to zoom in to the sixth decimal place. In our first data run, not all group members zoomed-in this far, which led to significantly higher uncertainty in our audio data.

5.1.3 Errors in Analyzing Video

Third, we did not have a standard method for measuring one period of a revolution. Some group members used Logger Pro to analyze the video recordings, while others used their stop watches to time the path of travel of the speaker with the raw video footage. Though both methods may have been reliable, the inconsistency added to the overall uncertainty, which is evident in the graph.

5.1.4 Errors in Data Collection

Fourth, and lastly, as a whole, our data collection methods were not entirely precise and reliable. This was because of, in part, the location of the experiment (indoors versus outdoors), having (or, in some cases, not having) a measuring device in the video frame as a reference point, and not having the string and speaker be in a plane with the recording device. The combination of these errors increased the overall uncertainty and led to more unreliable results.

5.1.5 Summary

All of these above problems contributed to the very high uncertainty in this first data run. We used uncertainty propagation to calculate the individual uncertainties for frequency and velocity. These equations will be discussed in the final data run analysis section below.

The abundance of errors and uncertainty begot a sense that we could improve our methods of analysis, which we think we did in our second data run, with apparent results.

Our final result from our preliminary data run graph in Figure 3 is the speed of sound as 59.6 $\frac{\text{m}}{\text{s}}$.

5.2 Final Data Run Analysis

The initial data run's errors were corrected in our final data run, culminating in graph that was much easier to analyze.

5.2.1 Overall Changes and Improvements

First, we made changes in the experiment set up and location. Some members changed their equipment, including the speaker, to have a higher quality tone for the frequency and a more accurate recording of the sound emitted. The members that initially did not include a tape measurement in the video recording for the preliminary data added it while performing the experiment. Some members also moved to more secluded areas that were more open with less background noise. In this iteration, we tried to have exactly 4000 Hz. However, even though most of us did not have 4000 Hz, we could account for this given we consistently measured the resting frequency for the sound source in each experiment.

Changes were also made in analysis to improve upon from the preliminary data run. We used similar techniques to analyze their raw video footage, all using Logger Pro video analysis. We also improved our waveform analysis, such as by counting the number of wave oscillations correctly from peak to peak. In calculations, we all checked each other's work to ensure that there were no calculation errors and proper significant figures in the final results.

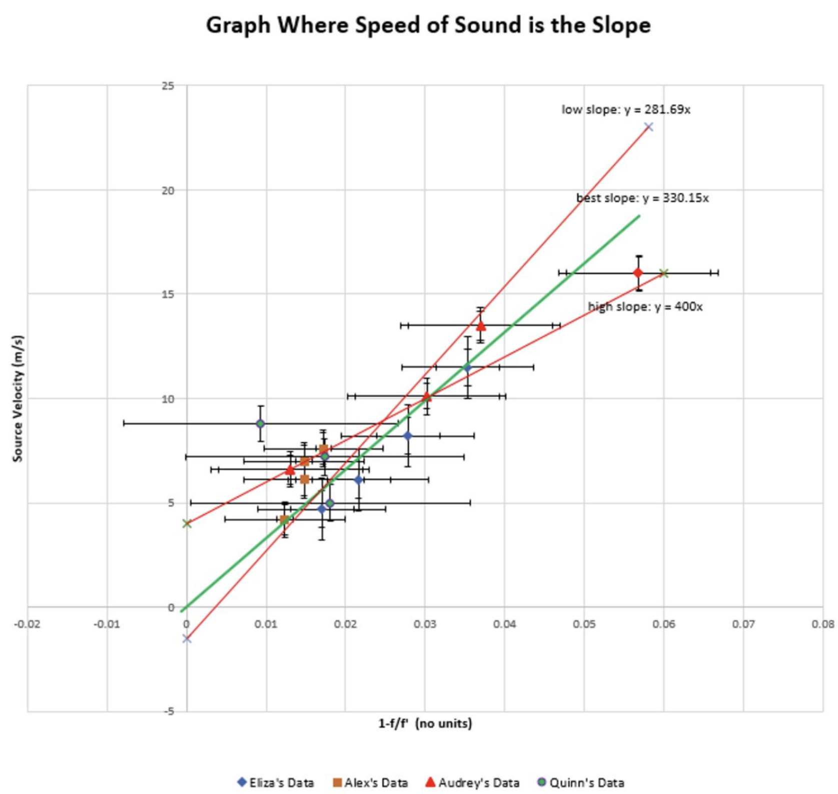

Figure 5: Results graph for Final Data Run

5.2.2 Results

The graphs from the two data runs are in stark comparison. The preliminary data run graph, Figure 3, has no discernible trend whereas the final data run graph, Figure 5, has a strongly linear trend. We were able to reach this positive goal together by correcting the previously stated errors.

In addition, our max and min slope lines used for calculating uncertainty, as discussed later, had negative and positive intercepts, respectively. This implies that the best fit line should have an intercept between those two intercepts. Given our rearranged equation for Doppler Effect, we expect that the best fit line will have a 0 intercept. Because this is within the range of the intercepts of the max and min slope lines, we have a higher confidence that our best fit line is consistent with what we expect.

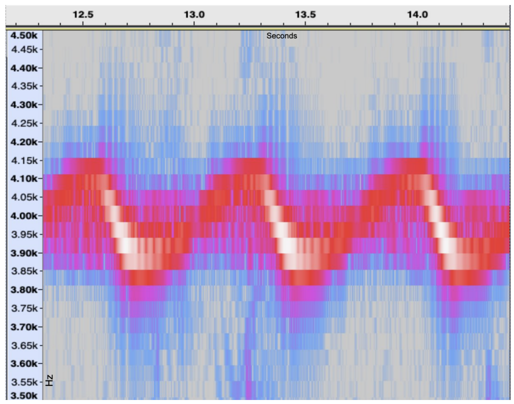

Figure 6: Example of spectrogram from an audio recording from Eliza. The vertical axis shows frequency in kHz, and the horizontal axis shows time in seconds

5.2.3 Improvements in Audio Analysis

We corrected our waveform analysis with the help of Professor Stephanik, who recommended methods for finding the ideal frequency using a binary search of point from the waveform using the spectrogram as a guide. An example of a spectrogram from Eliza's data run is shown in Figure 6. After applying those techniques, which included not counting as many waveforms (thus, less error), we found the waveform analysis went much more favorably, as is shown in the Data section.

We also all used the same methods while analyzing our data on Audacity. But instead of counting 100 waveforms, we decided to count 10 to 20 waveforms. We all also zoomed in to the fullest interval while analyzing the waveforms. Because the group used the same standard, our uncertainties more similar versus the first data run. This made it easier to place the best fit lines in our graph.

5.2.4 Improvements in Video Analysis

We used Logger Pro to measure the period by analyzing the data points, as seen in the Logger Pro analysis image in Figure 7. In contrast to our first data run, we all used LoggerPro in a consistent way to find more accurate velocities.

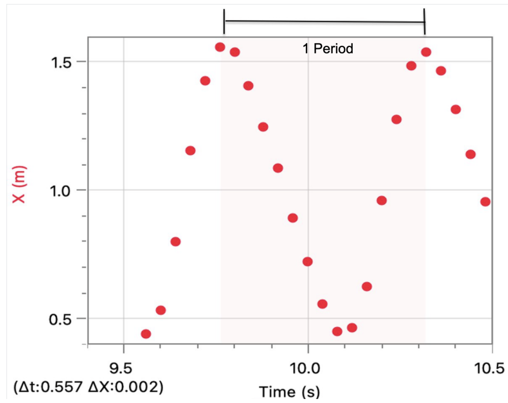

Figure 7: Example of Logger Pro video analysis points from Eliza

5.2.5 Improvements in Data Collection

We made our data collection much more precise. This, along with the data analysis, was a primary source of uncertainty. One way we improved our data collection was adding a measuring device (ruler, tape measure, etc.) into the recording frame. This allowed us to take a more accurate measurement of the string length, which helped in making the velocity more accurate. We also improved our data collection by altering the experiment. For example, Alex previously had problems with his data collection. In order to circumvent that problem, Alex devised a new way to collect data: he used a Radio Controlled car instead of spinning a speaker. The results were different than the other group members', but still produced a reliable result. Audrey, Eliza, and Quinn, on the other hand, continued to use the spinning method. They made sure to record their data away from walls, which may result in beat frequencies, and recorded an appropriate number of revolutions, between 10 to 20, to optimize the results.

5.2.6 Measuring Resting Source Frequency

Furthermore, in addition to measuring the Doppler shifted frequency when the speaker was in motion, we measured the resting source frequency (taken when the speaker was not in motion). We decided to take this additional measurement after the preliminary data run to ensure that everyone had about the same frequency as a base. We then used the resulting values from each member as a basis for each set of points we plotted.

5.2.7 Theoretical Speed of Sound

In addition, we needed to estimate a theoretical value for the speed of sound for our experiment. This is because we could not maintain a constant temperature between data collection locations. As temperature affects the speed of sound, this results in a different speed of sound for each location and time of day. Therefore, we calculated the range of possible speeds of sound given our temperature data. The, the value for speed of sound for our experiment in the final data run was the average of these individual speeds of sound, and the uncertainty is given by the average deviation of this range. Our final calculation yielded a theoretical value of the speed of sound as $343.7\ \frac{\mathrm{m}}{\mathrm{s}} \pm 0.8\ \frac{\mathrm{m}}{\mathrm{s}}$.

5.2.8 Uncertainty Analysis

In regards to calculating mathematical uncertainties, we estimated uncertainties using different techniques. A summary of these techniques is below. From these techniques that produced raw uncertainty values for our raw data, we used uncertainty propagation equations as follows to determine uncertainties for our x and y data points.

For the source velocity, given $v = \frac{s}{t}$, we calculated uncertainty using the following propagation:

$$\frac{\delta v_s}{v_s} = \frac{\delta s}{s} + \frac{\delta t}{t} \implies \delta v_s = v_s(\frac{\delta s}{s} + \frac{\delta t}{t})$$

Where v_s is the source velocity, s is the distance travelled (either the circumference for the circular motion experiment or the distance for the linear motion experiment) to travel, and t is the time elapsed to travel this distance.

For the frequency uncertainty, given that $f = \frac{N}{t}$, we calculated uncertainty using the following propagation:

$$\frac{\delta f}{f} = \frac{\delta N}{N} + \frac{\delta t}{t} \implies \delta f = f(\frac{\delta N}{N} + \frac{\delta t}{t})$$

Where f is a frequency from the waveform, N is the number of oscillations counted on the waveform, and t is the time elapsed over those oscillations.

Finally, for our final measurement uncertainty extracted from the slope of the graph, we used a slope uncertainty calculation technique. This involves finding the highest and lowest possible slopes that pass through the uncertainty bars. The difference between these divided by two gives the uncertainty of our final value.

From our final data run graph in Figure 5, we get a final value for the speed of sound as $330\ \frac{\mathrm{m}}{\mathrm{s}} \pm 60\ \frac{\mathrm{m}}{\mathrm{s}}$.

6 Conclusion

The goal of our experiment was to find the speed of sound by using the Doppler Effect. We did the experiment twice, incorporating improvements we noted could be made from the results of the first run in the final run. In each attempt, we analyzed the data to find the experimental value of the speed of sound. Our experimental results changed dramatically between our two data runs. The preliminary data run resulted in a speed of sound of 60 $\frac{\mathrm{m}}{\mathrm{s}}$. The estimated theoretical value of the speed of sound for our experiment is 343.7 $\frac{\mathrm{m}}{\mathrm{s}}$, with an uncertainty of 0.8 $\frac{\mathrm{m}}{\mathrm{s}}$. Therefore, our first results were in stark disagreement with the estimated theoretical value. Next, in our final data run, we calculated an experimental value for the speed of sound of 330 $\frac{\mathrm{m}}{\mathrm{s}}$ with an uncertainty of 60 $\frac{\mathrm{m}}{\mathrm{s}}$. Given our theoretical value for the speed of sound as stated above, the results of our final data run agree. We attribute this agreement to our improvements in data collection, video analysis, and audio analysis as described in the previous sections.

During our experiment, most of our uncertainty occurred in our data collection and analysis sections. Many small pieces of uncertainty culminated in a large uncertainty, as is evident in the graphs. However, as noted in the analysis section, we corrected most of our uncertainty in the final data run. This resulted in a more precise final product - one that agreed to the theoretical calculation of the speed of sound given our range of temperatures.

However, our experiment was not perfect, and we could have improved in several ways, even in our final data run. One way we could have improved was to improve our data collection. For instance, we could have used the same frequency tone, had the same string lengths, and used the same measuring device. Also, collecting more data might have made our data more reliable. Our analysis also could have be improved by having a uniform method for finding the highest frequency and using the same number of waveforms for the waveform analysis.

7 Addressing Presentation Questions

7.1 How Does Changing Source Velocity Affect Your Data?

In our experiment, we changed the source velocity while keeping everything else constant. This allowed us to get multiple data points for our graph to extract our slope, the speed of sound. From the Doppler Effect, the faster the source is moving towards the observer, the more the wavelength is compressed, and, therefore, the more the frequency increases.

7.2 Was There a Way to Measure How Fast the Speaker Was Traveling?

Yes, as explained in Theory section 2.5, if the source was moving in a circular path towards the observer, the tangential velocity of the source can be determined by the equation $v_s = \frac{2\pi r}{t}$, where r is the radius of the motion, and t is time elapsed. Similarly, for the linear motion experiment, the source velocity can be determined by the velocity equation for linear motion, $v_s = \frac{d}{t}$, where d is the distance traveled and t is time elapsed.

7.3 How did You Scale the Photograph in Logger Pro?

For the circular motion experiment, we recorded our entire data collection for each separate data set. Within each video, we had a ruler or meter stick to correctly scale our video for Logger Pro video analysis.

7.4 In Reference to Figure 2, Did You Click the Data Points When the Speaker Was at the Sides?

For the circular experiment, we each had our own method to determine the radius. As shown in Figure 2, Eliza chose to determine her radius by clicking the data points at the farthest distance the speaker reached at each side of the circular motion. The entire diameter was then calculated with Logger Pro, then divided by two to determine the radius of the circular path.

7.5 In Reference to Figure 7, In Your Final Analysis, Did You Use Multiple Revolutions, or Just One Revolution to Determine the Period?

Each of us in the circular experiment used differing methods to find the period. Figure 7 shows one period from Eliza's Logger Pro, but she used multiple periods, taking specific data points where her speaker was making the cleanest revolutions, to determine the period.

7.6 Did You Vary the Speed on Purpose to Get Different Points on the Graph?

Yes, see answer to section 7.1.

7.7 Did Anyone Conducting the Circular Motion Experiment Intentionally Try to Spin the Speaker with a Shorter Period in Order to Increase the Velocity?

We did not intentionally try to spin quicker. However, that happened unintentionally. Audrey spun the one meter radius at 16 m/s, which was faster than the rest of the group.

7.8 What Did You Mean When You Said "Off-by-One Error?

Off-by-one error refers to the error that occurred during the preliminary data run. In reference to Figure 4, some of us counted nine oscillations when they meant to count 10. This caused the frequency to be very off.

7.9 For Your Linear Distance Velocity, Did You Measure the Distance from Start to Finish, or Did You Find the Arc Length of the Distance the Car Traveled?

Since the velocity relative to the observer is all that matters for this experiment, we only needed to use the linear velocity for the car. We did need to ensure that the speaker was traveling directly towards the microphone though, for this reason.

7.9.1 Was This What the Chalk Lines Are For?

Yes, there were multiple chalk lines to determine the velocity of the car and to see if the car was still accelerating. It was. The error in measuring the distance, acceleration, and velocity were accounted for in uncertainty.

8 References

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9 Appendix 1: Raw Audio Data

Below are four data tables containing the complete raw audio waveform analysis data for each person collecting data in the final data run. In the tables, t_s represents the start time on the waveform, t_e represents the end time on the waveform, N represents the number of oscillations counted, and f' (if shown) represents the calculated frequency based off of the previous columns.

Audio Raw Data						
Set #	t_s (s)	δt_s (s)	t_e (s)	δt_e (m)	N	δN
1	2.311043	0.000015	2.315986	0.000015	20.0	0.05
2	1.846188	0.000015	1.851112	0.000015	20.0	0.05
3	0.933282	0.000015	0.938212	0.000015	20.0	0.05
4	4.744534	0.000015	4.749452	0.000015	20.0	0.05

Table 8: Alex's raw data from audio analysis

Audio Raw Data								
Set #	N	δN	t_s (s)	δt_s (s)	t_e (s)	δt_e (m)	f' (Hz)	$\delta f'$ (Hz)
1	20.0	0.1	6.16395	0.00001	6.16883	0.00001	4100	40
1	20.0	0.1	8.05313	0.00001	8.05803	0.00001	4080	40
1	20.0	0.1	10.49140	0.00001	10.49629	0.00001	4090	40
2	20.0	0.1	6.64345	0.00001	6.64827	0.00001	4150	40
2	20.0	0.1	8.39108	0.00001	8.39594	0.00002	4120	40
2	20.0	0.1	9.74721	0.00001	9.75204	0.00002	4140	40
3	20.0	0.1	10.44802	0.00001	10.45280	0.00001	4180	40
3	20.0	0.1	13.42865	0.00001	13.43346	0.00001	4160	40
3	20.0	0.1	15.72044	0.00001	15.72522	0.00001	4180	40
4	20.0	0.1	9.74800	0.00001	9.75275	0.00001	4210	40
4	20.0	0.1	11.40680	0.00001	11.41154	0.00001	4220	40
4	20.0	0.1	14.24967	0.00001	14.24507	0.00001	4350	40

Table 9: Audrey's raw data from audio analysis

Audio Raw Data					
Set #	t_s (s)	t_e (s)	N	f' (Hz)	$\delta f'$ (Hz)
1	14.848795	14.846332	10	4060	3
1	15.328143	15.325674	10	4050	3
1	15.322950	15.320484	10	4055	3
1	15.723453	15.720989	10	4058	3
2	14.848795	14.846332	10	4060	6
2	15.328143	15.3256740	10	4050	6
2	15.322950	15.3204840	10	4055	6
2	15.723453	15.7209890	10	4058	6
3	10.15397	10.1515290	10	4097	4
3	10.739398	10.736954	10	4091	4
3	11.348372	11.345935	10	4103	4
3	11.950563	11.948128	10	4107	4
3	12.593629	12.591190	10	4100	4
4	15.392069	15.38965	10	4134	4
4	16.758271	16.755849	10	4129	4
4	16.764159	16.761743	10	4139	4
4	17.408163	17.405739	10	4125	4
4	17.431754	17.429334	10	4132	4

Table 10: Eliza's raw data from audio analysis

Audio Raw Data						
Set #	t_s (s)	δt_s (s)	t_e (s)	δt_e (m)	N	δN
1	29.190500	0.000015	29.192957	0.000015	10.0	0.05
2	31.211041	0.000015	31.213500	0.000015	10.0	0.05
3	33.443854	0.000015	33.446333	0.000015	10.0	0.05

Table 11: Quinn's raw data from audio analysis