Name:____________________

Date:____________________

Doppler Effect II: Sound Waves in Air

Have you ever noticed that if a car with a horn blowing is moving past you rapidly that the sound waves emitted by the horn seems to change frequency? In 1842 an Austrian physicist, Hans Christian Doppler, observed and analyzed the same phenomenon for sound emitted by a passing train. Hence the phenomenon is known as the *Doppler Effect*.

A similar effect is found for the propagation of light and other electromagnetic waves from moving sources. In fact highway patrol officers use radar to measure Doppler shifts in radio waves so they can determine how fast vehicles are moving.

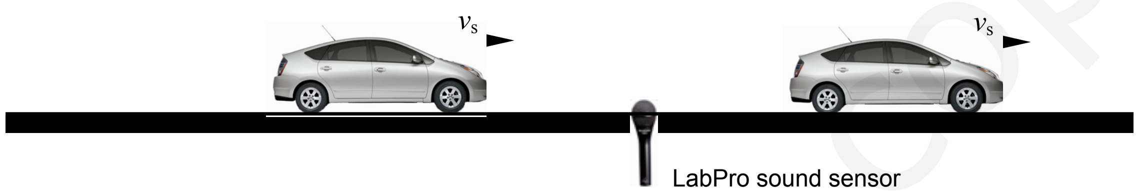

Fig. 1: A car is shown moving at a speed v_s past a sound sensor located at the side of a long straight road.

Suppose a driver is blowing her car horn and hears a predominant frequency denoted by f_0. What frequency, f_F will be detected by a microphone placed in front of the source of sound (consisting of the moving car horn)? Doppler proposed that the frequency, f_F detected in front of the source is given by

$$f_F = f_0 \frac{v_w}{v_w - v_s} \quad \text{(Eq. 1: frequency detected in front of a moving source)}$$

where v_w is the speed of the sound wave propagation in air and v_s is the speed of the moving source from which the sound wave emanates.

Similarly, Doppler predicted that the frequency of waves propagating behind a source of sound that moves away from an observer at speed v_s can be determined using the equation

$$f_B = f_0 \frac{v_w}{v_w + v_s} \quad \text{(Eq. 2: frequency detected behind a moving source)}$$

We have created movies of a honking car moving fairly rapidly on a straight level road past a stationary microphone. We have recorded the sound waves emanating from the car's horn separately using a sound sensor attached to the *LabPro* interface, operated by the roadside observer. You will be working with these files in this exercise.

Your goal in this assignment is to verify that the Doppler Equations, shown above, can be used to predict the ratio (f_F / f_B) of the apparent car horn frequencies before and after the car passes the microphone. To complete this assignment you will need to: (1) Use Equations 1 and 2 to derive an equation for this ratio as a function of the speed of sound waves in air (v_w) and the speed of the moving car horn (v_s), and then (2) use Logger *Pro* to determine the value of v_s using the movie of the passing car.

1. Preliminary Questions

> **Note:** You will receive FULL CREDIT FOR EACH PREDICTION you make in this preliminary section whether or not it matches conclusions you reach in the next section. As part of the learning process it is important for you to compare predictions with your outcomes. PLEASE DO NOT CHANGE YOUR PREDICTIONS.

(a) Open the movie entitled <CarHornDoppler.mov> and play it. This video clip was recorded by a digital video camera that was placed perpendicular to the road and 10.0 meters away from the center of the car just as it passes the sound sensor in the center of the frame as shown in Fig.2. The sound dubbed into the *Car Horn Doppler* movie was recorded at the roadside by this sound sensor. What happens to the frequency of the car's horn as the car moves from an initial position to the left of the camera to a final position to the right of the camera? Does it remain constant or does it change? Explain.

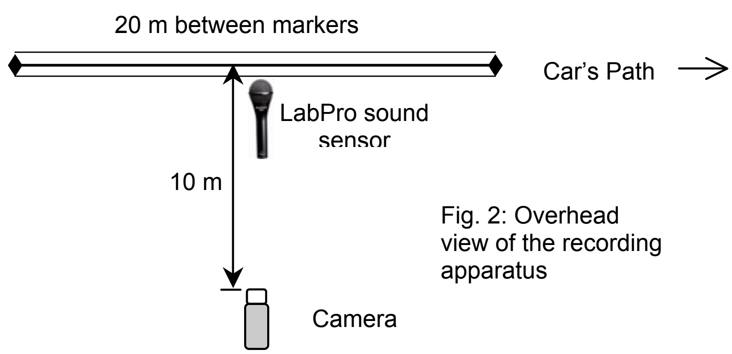

Fig. 2: Overhead view of the recording apparatus

Grader: *Any reasonable observation is acceptable. Students will probably say that the sound goes from a higher sound or higher frequency as it approaches to a lower sound or lower frequency as it recedes from the sound sensor. Often students mix up the loudness and softness with the frequency shift and say that the horn becomes louder and softer. It's important that they say this so the misconception can be addressed.*

(b) Replay the move and listen carefully to the sound as the car passes the observer. You should hear a pattern similar to one you might recall for a train blowing its whistle or that of a fire engine's siren as either approaches and then recedes from you. Give a qualitative explanation for the nature of the frequency change recorded by the roadside sound sensor (microphone).

Grader: *Most students should describe the change in the frequency as the sound appears to have a higher pitch or a higher frequency as it approaches the observer and a lower pitch or lower frequency as it moves away from the observer.*

2. Activity-Based Questions

Experimental verification of the Doppler Equations:

(a) Use the Doppler Equations to derive an equation for the ratio f_F/f_B as a function of the speed of sound waves in air (v_w) and the speed of the moving car horn (v_s). Show your work.

$$\frac{f_F}{f_B} = \frac{f_0}{f_0} \times \left(\frac{v_w}{v_w - v_s}\right) \Big/ \left(\frac{v_w}{v_w + v_s}\right) = \frac{v_w}{v_w - v_s} \times \frac{v_w + v_s}{v_w}$$

$$\frac{f_F}{f_B} = \frac{v_w + v_s}{v_w - v_s}$$

(b) Open Logger *Pro* file entitled <LPh18-2.cmbl>, which has a shortened version of the movie, inserted in it. Determine the speed of the car and its blowing horn "sound source," (v_s). Explain what you did to find (v_s). Record your value for (v_s) in the box below.

To find the speed of the car, which is the speed of the blowing horn "sound source," v_s, the student should state that they will perform a video analysis of the short movie by clicking on a point on the car. After gathering the points and scaling the movie, they will probably perform a linear fit on the data illustrated on the graph. An alternate method would be to export the data to Excel and perform a statistical analysis on the v_x values. Their results should be within less than 2% of this value.

$$\boxed{v_s = \underline{\ 20.4\ }\ \text{m/s}}$$

(c) It turns out that the speed of sound in air (v_w) depends on the air temperature (T_c) and can be calculated using the equation[1]

$$v_w = 331.45\sqrt{1+\frac{T_c}{273.16}}\ \text{m/s} \qquad \text{(Eq. 3)}$$

When the movie of the horn blowing car was made, the air temperature (T_c) was recorded as 27.2°C. What was the speed of sound in air (v_w) on that day? Show your calculation!

$$v_w = 331.45\sqrt{1+\frac{T_c}{273.16^\circ\text{C}}}\ \text{m/s}$$

$$v_w = 331.45\sqrt{1+\frac{27.3^\circ\text{C}}{273.16^\circ\text{C}}}\ \text{m/s}$$

$$v_w = 347.6\ \text{m/s}$$

(d) Find the expected value of the ratio f_F/f_B in terms in terms of your calculated value speed of sound in air (v_w) and your measured value of the speed of the sound source (v_s). **Hint**: Use the equation you derived in Part 2(a). Show your calculations and round your answer to 3 significant figures.

$$\frac{f_F}{f_B} = \frac{v_w + v_s}{v_w - v_s}$$

$$\frac{f_F}{f_B} = \frac{347.6\frac{\text{m}}{\text{s}} + 20.4\frac{\text{m}}{\text{s}}}{347.6\frac{\text{m}}{\text{s}} - 20.4\frac{\text{m}}{\text{s}}}$$

$$\frac{f_F}{f_B} = 1.12$$

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[1] Dennis A. Bohn, "Environmental Effects on the Speed of Sound", Presented at the 83rd Convention of the Audio Engineering Society, New York, October 16-19, 1987. Http://www.rane.com/pdf/eespeed.pdf

(e) *Determining Your Ratio with Direct Frequency Measurements*: This next activity is a direct test of the validity of the Doppler Equations. We have recorded the sound pressure using the LabPro sound sensor placed at the side of the road for about one second before the car passes the sound sensor and for about one second after the car passes this sensor. In each case we have used a *Fast Fourier Transform* analysis (FFT) of the sound pressure waves to help you find the predominant frequency just before (f_F) and just after (f_B) the car passes the roadside sound sensor microphone.

(f) Start by opening the Logger *Pro* file entitled <f_before & after.cmbl>. Look for the largest peak on the FFT graph describing the frequencies between 0 s and 1 s to find the predominant frequency just before (f_F) the car passes the sensor. Change the scale on the horizontal axis so that you see this region in more detail. You can accomplish this by selecting the *Additonal Graph Options* -> FFT Graph Options from the *Options* menu or by double clicking on the FFT Graph to reset the frequencies displayed so that you focus only on the highest amplitude frequencies. Next, use the *Examine* Tool to find the predominant frequency just before (f_F) the car passes the sensor. Repeat the procedure between 2 s and 3 s to find the predominant frequency just after (f_B) the car passes the sensor. Summarize your results in the appropriate spaces below and calculate the ratio f_F/f_B.

FFT Max 0s to 1s: f_F = __609.5 Hz

FFT Max 2s to 3s: f_B = __545.3_ Hz

Direct: f_F/f_B = _1.12___

3. Reflections on Your Findings

(a) How did the ratio f_F/f_B that was determined from the Doppler Equations (in Part 2 (d)) compare to the ratio determined from direct measurements (in Part 2(e))? Find the percent difference between the two results.

Grader: *Students should find very close agreement between the two methods. To 3 significant figures, the answers are the same. Students should find not much more than a 1% difference between the ratio of the frequencies determined by the Doppler equations and the comparison with the ratio determined from the actual FFT of the recorded sound pattern.*

(b) Suppose you are assisting a policeman, who is sitting in stationary cruiser and is pointing his radar gun at the approaching car. His detector shows a read-out of the car's speed. Using the physics you know, describe how you could use your data to calculate the speed of the moving car (v_s) to help him check the reliability of his equipment.

$$f_F = f_0 \frac{v_w}{v_w - v_s}$$

Rearranged and solving f or v_s:

$$v_s = v_w \frac{(f_F - f_0)}{f_F}$$

After choosing the Doppler equation for an approaching wave and rearranging it to solve for v_s, *I would find the velocity of the sound wave at this temperature using the equation relating the sound wave to the temperature and then substitute in all the known values to solve for the speed of the vehicle to check it against the radar detecting equipment.*