Speed of Light in Air

Introduction
Light can travel a distance comparable to seven and one-half times around the Earth in one second. The first accurate measurements of the speed of light were performed by using well-collimated, continuous light beams which were transformed to pulsed beams by some mechanical device. Fizeau used a rotating toothed wheel and Michelson used a rotating mirror to create the pulsed beams. By measuring the time difference between the pulsed light beams which traveled different distances, Fizeau and Michelson were able to measure the speed of light to within 0.2% and 0.02% respectively.

Procedure
Wear laser safety goggles. Handle goggles with care, avoid touching the lens. Do not look directly into the laser beam or shine the laser in anyone’s eyes. Do not touch the mirrors. They are extremely delicate.

In this experiment, a laser will be the source of collimated light. A beam splitter, which reflects a portion of the beam and allows a portion to pass through, is used to create two separate beams. The reflected beam is directed along a short path to the photodetectors. The beam that passes through the splitter is directed down a long path to the photodetectors (see Figure 1).

The intensity of the laser is modulated at a frequency of 2 MHz. When measured by a photo-detector, which has been connected to an oscilloscope, the laser output will appear on the scope as a 2 MHz waveform. The waveform on channel 1 comes from the beam following the short path striking a photo-detector. The waveform on channel 2 comes from the beam following the long path striking a photo-detector. The time difference between the peaks of the two waveforms can be used to determine the time it took the beam to travel the additional distance of the long path.

Figure 1 Beam paths
Questions
Use the difference in the distance the two beams travel and the difference in the amount of time it takes for them to arrive at the photo-detectors to calculate the speed of light. Compare your calculated value for the speed of light to the accepted value.
Speed of Light in a Dense Material

Introduction
In another portion of today’s lab you will measure the speed of light in air, that is to say the speed with which a light signal propagates through air. Light is an electromagnetic phenomenon; it consists of oscillating electric and magnetic fields that form a traveling wave. When you perform that measurement you should find that the speed of light in air is very close to the universe’s ultimate speed limit of $2.98 \times 10^8$ m/s, the speed of light in a vacuum or $c$. In fact the two speeds are practically indistinguishable. It takes a finite amount of time for electromagnetic phenomenon to propagate in other materials as well. For instance, the electrical signals running from your ipod to your headphones travel at a speed significantly less than $c$. This makes a certain amount of intuitive sense – in air or a vacuum there are relatively few particles for electric and magnetic fields to interact with. However, in a dense material like the copper conductor in your headphone wires there are a great deal of electrons and atoms to interact with. You might expect those interactions to retard the propagation of electric and magnetic signals. In this lab you will get the opportunity to measure the propagation speed of signals in high quality electrical cable, the very kind used in particle and nuclear physics experiments to carry signals between detectors and electronics.

Apparatus
- Function generator
- Oscilloscope
- Long, unknown length of RG58 coaxial cable with BNC connectors
- Long, known length (approximately 500 feet) of RG58 coaxial cable with BNC connectors
- Two BNC tees
- One 50 Ohm BNC terminator
- Short length of RG58 coaxial cable with BNC connectors

Procedure
In this lab you will use the oscilloscope to measure how long it takes a signal to travel from one end of a long length of cable to the other. Put a BNC tee on each of the input channels of the scope. Use the short length of cable to connect the function generator output to one of the tee inputs on channel 1. Connect the long cable between channel 1 and 2 inputs. Put the 50 ohm terminator on the other channel 2 tee input. (The purpose of the terminator is to prevent the signal from being reflected back down the cable. You can take it off and look at the resulting signal if you want.) Set the function generator for square wave output, choose an output frequency of around 1 kHz, and turn the output up. You should see a square wave on each channel of the oscilloscope with the frequency you set. (You may need to push the “Autoset” button once to get the oscilloscope to show anything.) If you zoom the time in and look at the rising edge of the square wave (the part where the voltage is going up) you should see that the signal on channel 2 is delayed slightly from the signal on channel 1 even though the signal is from the same
source (the function generator). Of course, this delay occurs because the signal has to get through that long length of cable between channels 1 and 2. Measure that delay time. (You may find it helpful to use the “Cursor” function of the oscilloscope.)

**Questions**

1. Measure the propagation time through the known length of cable and use that information to determine the propagation speed in this type of cable (coaxial RG58). The manufacturer claims that the propagation speed through cable of this type is 66% of the c. Do you agree with the manufacturer? Try to get a numerical estimate of the uncertainty on your measurement. (You might want to consider how well you can measure the propagation time.)

2. Use this apparatus to determine the length of the unknown length of cable. (Do not unspool the cable and use a tape measure!) It is the same type of cable as the known length (coaxial RG58). Make sure you describe your technique.

3. If you take the 50 ohm terminator off of channel 2 then once the signal gets to channel 2 it will reflect back down the cable the way it came and you should eventually see it on channel 1 again. Try it and describe what you see. Can you explain the structure you see on channel 1? How would you measure the propagation speed of the wave using just the information on channel 1 (pretend that channel 2 is broken). Perform the measurement and compare to your previous value.
Speed of Sound in Air

**Introduction**
In the other portions of today’s lab you will measure the propagation speed of electromagnetic phenomena through a couple of different materials: air and coaxial electrical cable. In this part you will explore the propagation of another type of signal – an acoustic one. The sound waves that your ears detect are really pressure waves propagating through air. The air is compressed and rarified so that there are regions of slightly lower and higher pressure. As anyone who has flown in an airplane, driven over a mountain, or driven into a deep valley can attest your ears are extraordinarily sensitive to pressure differences. Your eardrum detects the pressure differences in the sound wave and transmits the signals to your brain electrically. In this lab you will measure the propagation speed of pressure waves through the air.

**Apparatus**
- Speaker
- Microphone
- Function generator
- Audio amplifier
- Oscilloscope
- Two meter stick
- Thermometer

**Procedure**
The function generator will be used to drive the speaker and create an audible tone. Set the function generator for sine wave output and choose a frequency somewhere between 500 and 1000 Hz. The frequency generator output should also go to channel 1 of the oscilloscope. Once you have the signal patched in and the function generator running, pushing the “Autoset” button to get good default oscilloscope settings.

Adjust the microphone so it is pointing towards the speaker and is about 20 cm away from it. The microphone will play the role of your eardrum. It will detect the pressure wave and transform it into an electrical signal. Plug the microphone output into the audio amplifier and from there into channel 2 of the oscilloscope. Adjust things so you can see both traces on the oscilloscope at once. You should see two sinusoidally varying waves on the oscilloscope and in all likelihood they will be slightly out of phase.

From the waves lab you did in General Physics I you know that the velocity of a traveling wave, like our sound wave, is equal to its frequency times its wavelength, \( v = f \lambda \). The function generator determines the frequency of the wave and the speed of sound determines the wavelength. In order to determine the speed \( v \) you must measure the wavelength of the pressure wave. Adjust the position of the microphone so that the two sinusoidal waves are in phase and record the distance between the microphone and the speaker. Now slowly move the microphone away from the speaker. You should see the
trace on channel 2 (the microphone) moving relative to the trace on channel 1 (the function generator). When the waves are in phase again the microphone will have moved one full wavelength. Record the new speaker-microphone distance.

**Questions**

1. Use the information you gathered to determine the speed of sound in air. Try to provide a numeric estimate of the uncertainty on your determination. The accepted value for the speed of sound is $331.4 \pm 0.6 \, T \, \text{m/s}$ where $T$ is the air temperature in °C. Do you agree or disagree?

2. In order to perform this measurement you picked an arbitrary frequency for the wave. The underlying assumption implied by this is that the speed of sounds is not frequency-dependent, e.g. the speed of sound does not increase as the frequency increases. How would you test this assumption? Go ahead and prove or disprove this assumption.