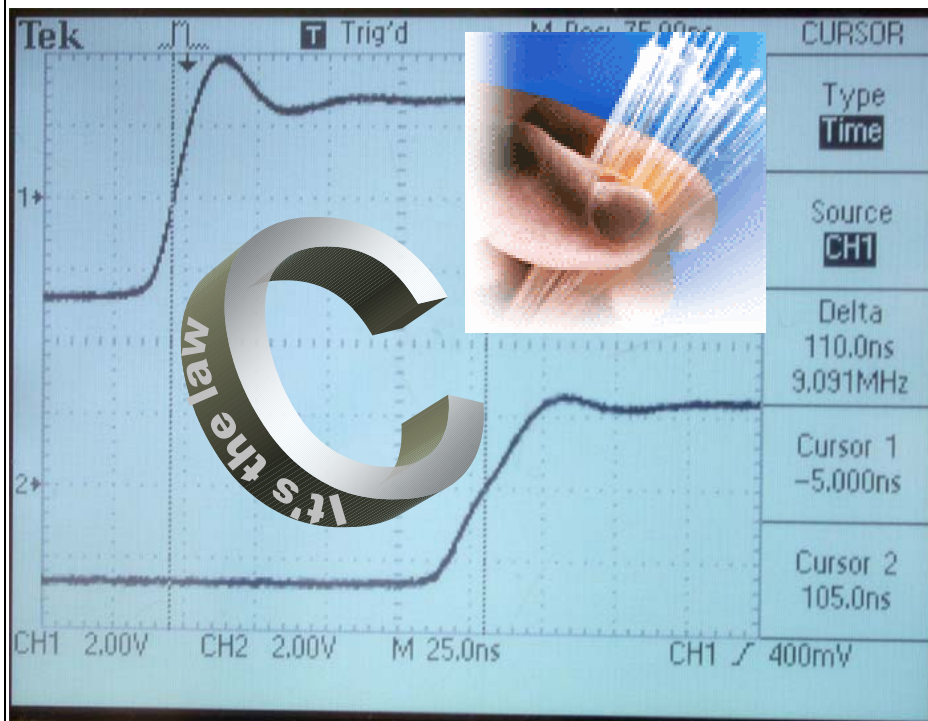


# EXPERIMENT S1:

## *Speed of Light – Time of Flight Method*



### Objectives:

- Measure the speed of light in air.
- Measure the speed of light in an optical fiber.
- Measure the speed of an electrical pulse in a coaxial cable to verify that it is slower than  $c$
- Learn to use oscilloscopes and pulse generators.

## Introductory Material

The speed of light in a vacuum,  $c$ , has an accepted value of 299,792,458 meters per second. This is the fastest speed that information can travel.

In this experiment, you will use “time-of-flight” methods to measure the speed of light. The original attempt to do this was by Galileo, who used flags and lights, with human operators doing the timing measurements. This wasn’t fast enough, so he found that the speed of light was infinite.

In Part I and II you will use an oscilloscope to make the measurements much faster than Galileo could. A light-emitting diode will flash, and then you will detect the flash of light after it travels through air or an optical fiber. After the light pulse has traveled a distance  $x$ , it will be detected by an optical detector. The detector will produce an electrical pulse that you will detect using an oscilloscope.

The oscilloscope plots voltage vs. time on a display. It allows you to measure the time required for the pulse to travel through a given distance. By repeating this for a long distance and a short distance, and subtracting, you will arrive at a time  $\Delta t$  to travel a distance  $\Delta x$ . This will allow you to compute the speed. If you have only one data point, you will compute the speed directly as  $\Delta x / \Delta t$ . If you have more than one data point, you will plot  $\Delta x$  vs.  $\Delta t$  and fit to a straight line; the slope will be the speed.

The optical fiber you will use is a “multi-mode” fiber. In other words, the fiber diameter is much larger than the wavelength of light. In contrast, telecommunications companies usually use single-mode fiber, which is harder to use but has the advantage that the speed of propagation is defined more distinctly. That isn’t necessary here, because we’ll use a short distance, compared to the inter-city distances where single-mode fiber is needed.

When light or other electromagnetic radiation travels through a medium, like a plastic optical fiber, it will have a slower speed than  $c$ , the speed of light in a vacuum. You will calculate the ratio  $n = c / v$ , where  $v = \Delta x / \Delta t$  is the result of your time-of-flight measurement.

In Part III you will measure the speed of an electrical pulse in a coaxial cable. The reason we do this is because data is usually transmitted this way, and you will be able to verify that this information travels slower than  $c$ , the speed of light in a vacuum.

## **Pre-Laboratory Questions**

- (1) Calculate the time-of-flight you expect for light to propagate a distance of 20 m in (a) vacuum and (b) a medium with an index of refraction  $n = 1.5$ . Express your answer in nanoseconds (ns).
  
- (2) In telephone calls using a satellite, you sometimes can hear a delay in the response of the other person. Satellites are usually either in low-Earth orbit (just above the atmosphere) or much higher in geosynchronous orbit. The latter is at an altitude of 35,785 kilometers (22,236 miles), where the satellite completes one orbit in exactly one day. Because the orbital velocity matches the spin rate of the Earth, a satellite in a circular equatorial geosynchronous orbit appears to hover motionless over a single location on the equator. The total delay in hearing your correspondent's reply, due to the finite speed of light, is due to two round trips. If you and your correspondent were located nearby, and on the equator, the only distance involved is the distance from you to the satellite, the total distance corresponding to the delay is  $4 \times 35,785$  km. Calculate this delay, assuming the radio signal travels at the speed of light in a vacuum. Report your answer in units of seconds, and discuss in one sentence whether this delay is long enough for you to notice. Identify at least one factor that could cause the actual delay to be longer than what you calculated.

## Equipment List

### ***Part I***

### ***Part II***

Digital Storage Oscilloscope  
Speed of Light Apparatus  
20-m and 15-cm length optical fiber cables  
(1 mm plastic fiber clad in a 2 mm  
diameter jacket)  
50  $\Omega$  splitter

### ***Part III***

Digital Storage Oscilloscope  
Function generator (BK Precision 4017)  
BNC TEE



BNC cables:

- three long cables of various lengths, roughly 10 m, 20 m, and 30 m
- one short cable, < 2 m

50  $\Omega$  terminator

The apparatus will be set up in stations, so that a student will move from one table to another after completing a part of this experiment. The experiment can be completed in any sequence.

An asterisk indicates that an item is described in the Instrument Glossary.

## **Experimental Procedure**

### Part I: The Speed Of Light In Air

*The manual for this part has not yet been written.*

Part II: The Speed Of Light In Optical Fiber

Caution:

- Be careful not to break the fragile insulators on the terminals on the circuit board.
- Do not allow the probe to hang over the edge of the table, because it would be too easy to bump the probe and damage the terminals.

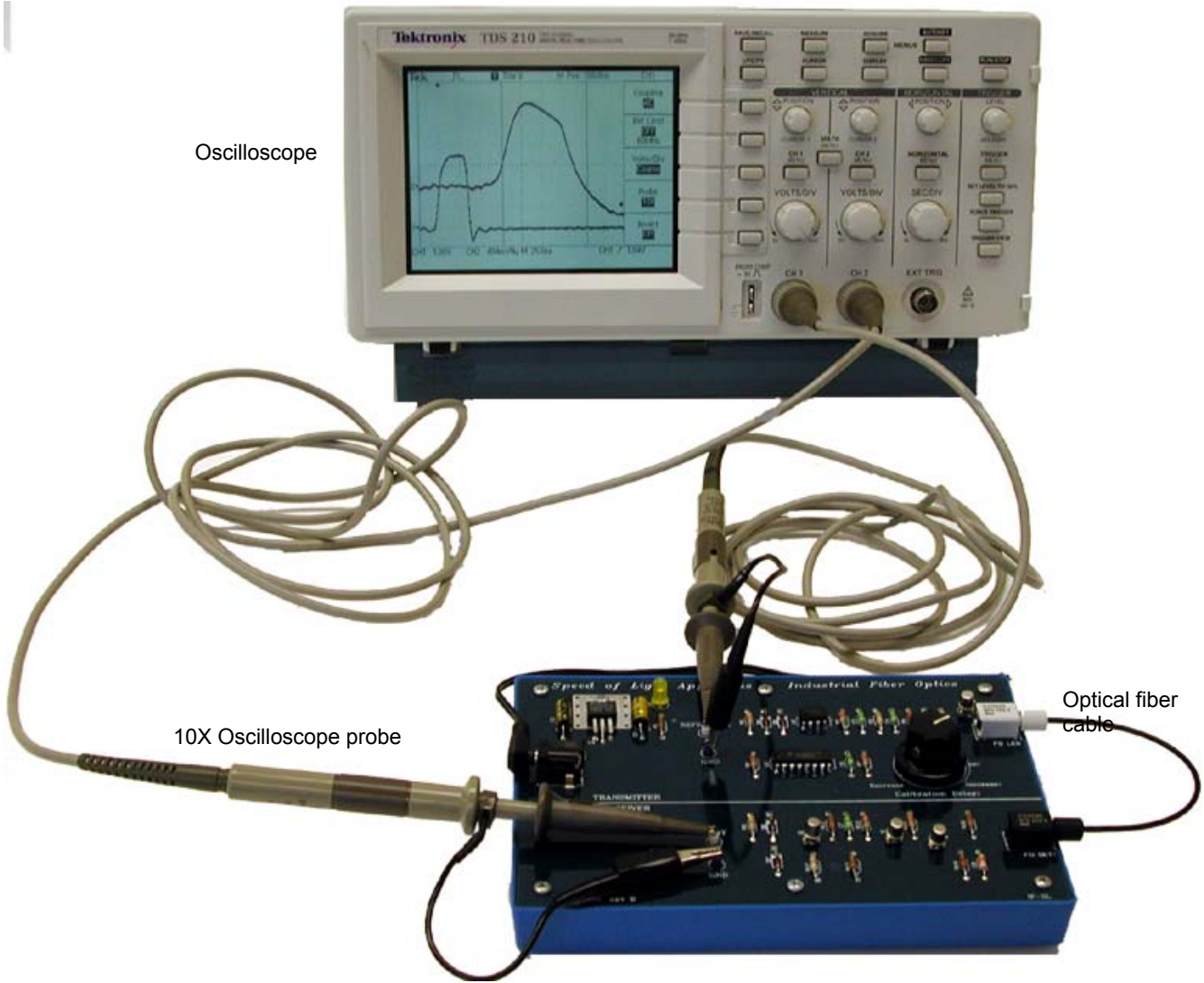


Figure II-1. Setup for speed of light measurements using fiber optics.

Exp. S1: Speed of Light (Time of Flight Method)

Set up the Speed of Light Apparatus circuit board as follows:

- Insert the ends of the 15-cm long fiber cable into the two chucks on the circuit board. Tighten but do not over-tighten the chucks. See Figure II-2.
- Turn the “Calibration Delay” knob as shown in Figure II-3 to the 1-O’Clock position initially. (You will adjust this again later.)
- Connect two oscilloscope probes to the Speed of Light Apparatus, as shown in Figure II-4.

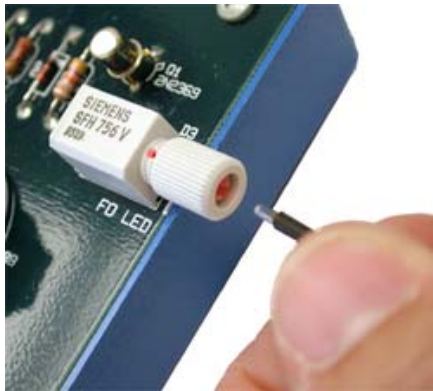
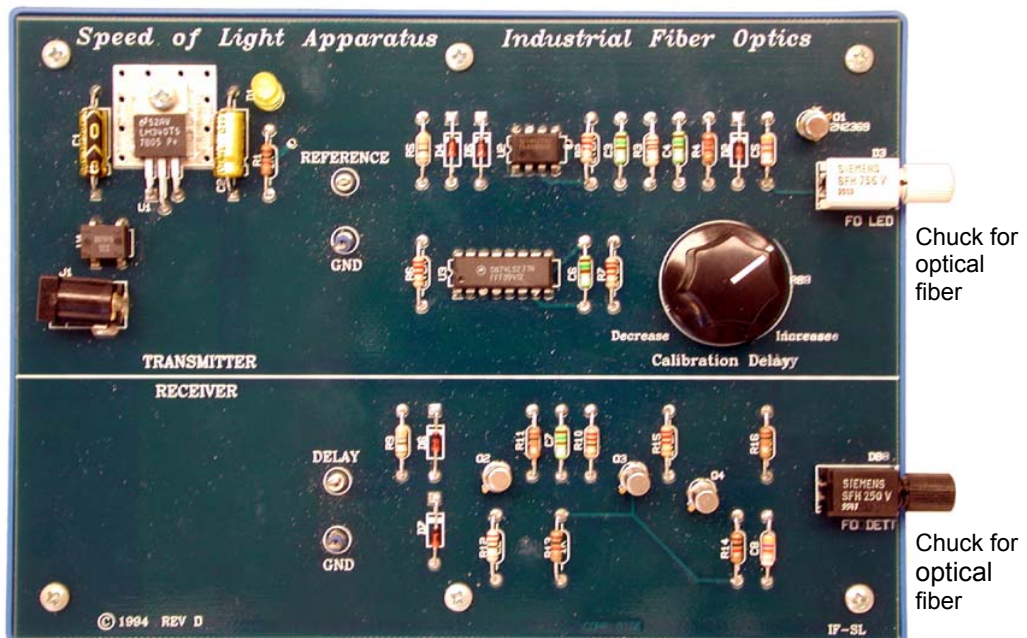


Figure II-2. Insert the fiber into the chuck. Insert it all the way, then tighten the chuck, but do not overtighten it. Be careful not to scratch or damage the plastic fiber tip.



Figure II-3. Calibration delay. This knob on the circuit board adds a delay to the receiver signal so that you can position the receiver pulse at a convenient place on the scope display. Initially you should turn this knob to the 1-O’Clock position.



Circuit board

Exp. S1: Speed of Light (Time of Flight Method)



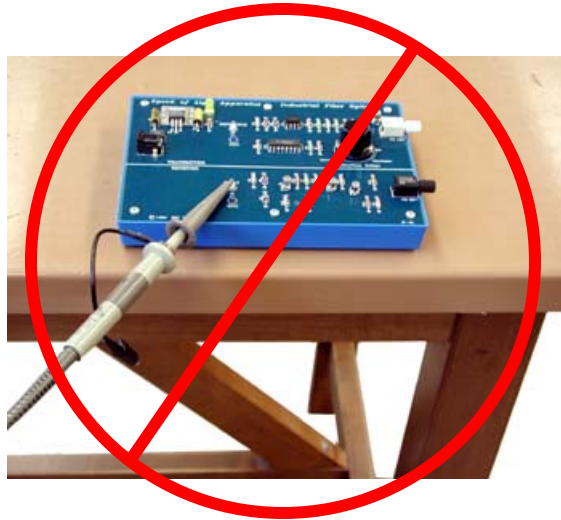
Probe tip



Terminals on circuit board. Be careful not to break them.



Probe tip, connected to terminals on circuit board. The alligator clip is connected to the GND terminal. Lay the tips on their sides, as shown here.



Do not allow probe to hang over the edge of table. This might break the terminals on the circuit board.

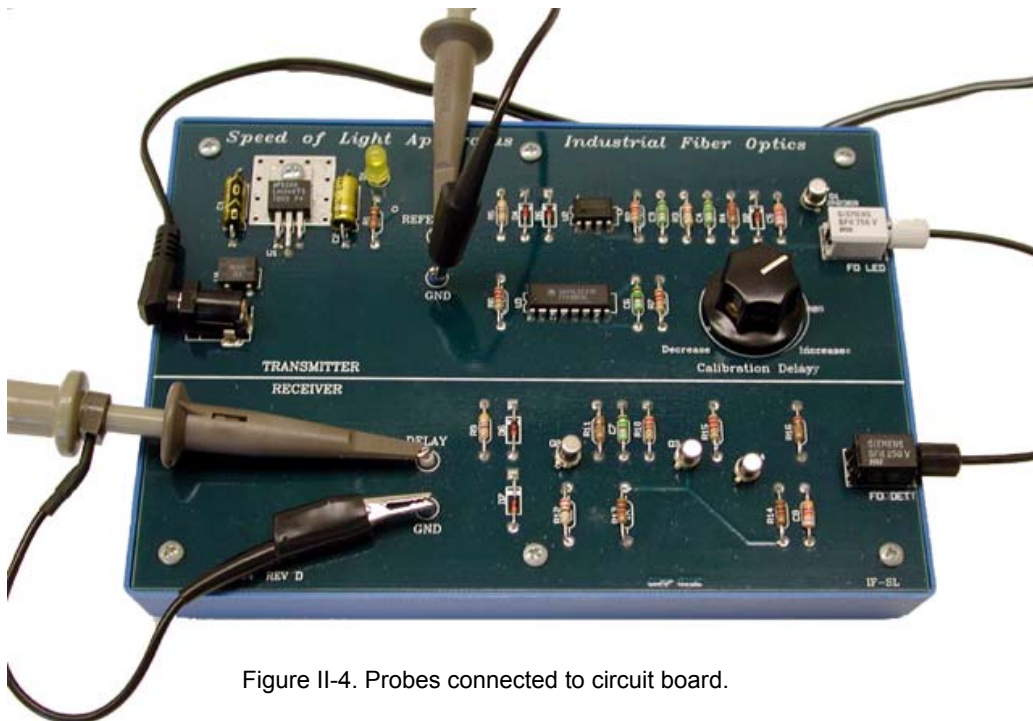


Figure II-4. Probes connected to circuit board.



Set up the oscilloscope:

- Connect the oscilloscope probes to the oscilloscope:
  - CH1 should be the probe connected to REFERENCE terminal on the circuit board
  - CH2 should be the probe connected to DELAY terminal on the circuit board

- Adjust the scope's CH1 menu settings:



- Press the CH1 MENU button.
- Verify that all the menu selections are as shown in the left panel of Figure II-5. If they aren't, then use the menu buttons to adjust them.

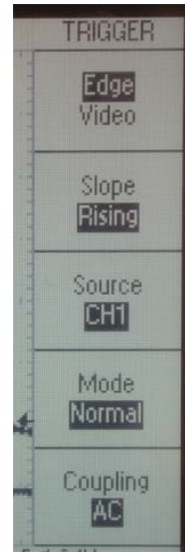
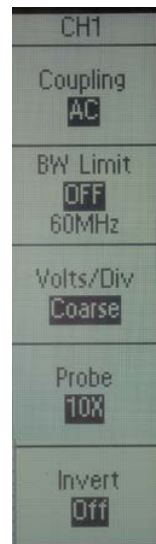


Figure II-5. Menu screens for setting up oscilloscope.

- Adjust the scope's CH2 menu settings:



- Press the CH2 MENU button.
- Verify that all the menu selections are as shown in the middle panel of Figure II-5. If they aren't, then use the menu buttons to adjust them.

- Adjust the scope's trigger menu settings:

- Press the Trigger MENU button.
- Verify that all the menu selections are as shown in the right panel of Figure II-5. If they aren't, then use the menu buttons to adjust them.

- Press the CH1 button to finish with the menus.

- Adjust the scope's vertical scales:

- Examine the display of the CH1 and CH2 Volts/Div scale, indicated at the bottom of the oscilloscope display. See Figure II-6.
- Verify that CH1 Volts/Div is 1.0 V and CH2 Volts/Div is in the range 350 to 450 mV, as shown in Figure AAA. If they aren't, then turn the CH1 or CH2 Volts/Div knobs



to adjust. You will make a final adjustment to the CH2 setting later.



Figure II-6. VOLTS/DIV settings.

Exp. S1: Speed of Light (Time of Flight Method)

CH1 1.00V CH2 404mV M 25.0ns

Figure II-7. SEC/DIV setting.

- Adjust the scope's horizontal scale:
  - Examine the indicator at the bottom of the oscilloscope display.
  - Verify that the time scale is 25.0 ns per division, as shown in Figure II-7. If it isn't, then turn the SEC/DIV knob to adjust.
  - Examine the "M Pos" indicator at the top-right of the oscilloscope display. Verify that it indicates M Pos: 100.0 ns, as shown in Figure II-8. Note that this should not be -100.0 s. If necessary, adjust the HORIZONTAL POSITION knob.
  - Examine the trigger threshold level at the bottom-right of the oscilloscope display. Verify that it indicates a value somewhere in the range 920 mV – 1.12 V, as shown in Figure II-9. If it isn't, then adjust the TRIGGER LEVEL knob.

M Pos: 100.0ns

Figure II-8. Horizontal position setting.

CH1 / 1.04V

Figure II-9. Trigger threshold level.

- Adjust the vertical positions of the waveforms:
  - Plug in the Speed of Light Apparatus, so that its power is on.
  - You should see two waveforms displayed on the oscilloscope. If one of the waveforms is missing, press the CH1 or CH2 button. If the amplitude of the peak in the CH2 peak waveform is much smaller than 4 cm on the display, then check to see if the fiber ends are fully inserted into their chucks.
  - Press the CH1 MENU button.



- Turn the Position knob for CH1 until the baseline of the waveform, as indicated by the 1\* marker on the left of the scope

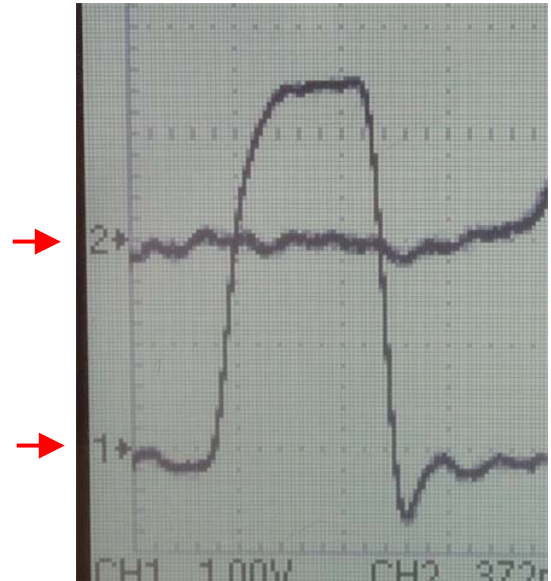


Figure II-10. Adjusting the vertical position on the oscilloscope.


You should adjust the two vertical position knobs until the two markers on the left are at the positions shown:

- 1 at 1 cm above the bottom
- 2 at 3 cm above the bottom

display, is exactly 1 cm from the bottom of the display, as shown in Figure II-10.

- Press the CH2 MENU button.



- Turn the Position knob for CH2 until the baseline of the waveform, as indicated by the  marker on the left of the scope display, is exactly 3 cm from the bottom of the display, as shown in Figure II-10.

- Adjust the vertical scale for CH2:
  - Press the CH2 MENU button.
  - Adjust the CH2 VOLTS/DIV knob until the peak height is exactly 4 cm on the display, as shown in Figure II-11.

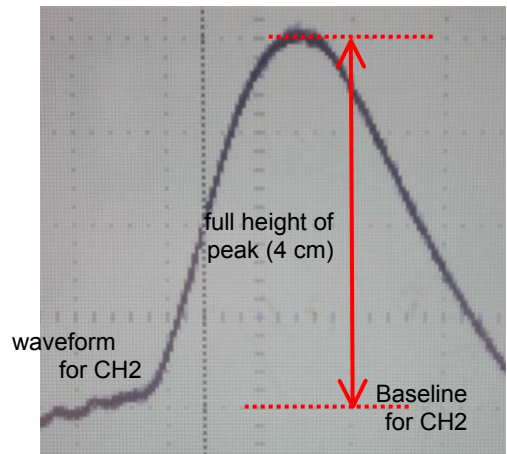


Figure II-11. Adjusting the VOLTS/DIV for CH2, so that the peak has a height of 4 cm. Note the dotted gridlines on the scope display. (Earlier you should have adjusted the VERTICAL POSITION of CH2 so that its baseline is 3 cm from the bottom of the display, as shown in Figure EEE. )

Adjust the Speed of Light Apparatus:

- Adjust the “Calibration Delay” knob on the circuit board until the peak of CH2 is approximately centered halfway between the left and right edges of the oscilloscope display. Thereafter, never touch this knob.

Make the time-of-flight measurements.

You will use the oscilloscope’s cursors to measure the time of the pulse. Because the pulse is rather wide as compared to the time we wish to measure  $\Delta t$ , we will choose a specific point of the pulse to measure: the point on the leading edge of the pulse where the amplitude is exactly  $\frac{1}{2}$  its maximum. We will measure the time of this point on the pulse for the short fiber and then again for the long fiber. The difference will be the time-of-flight,  $\Delta t$ .



- Press the oscilloscope’s CURSOR button. This will produce two vertical lines on

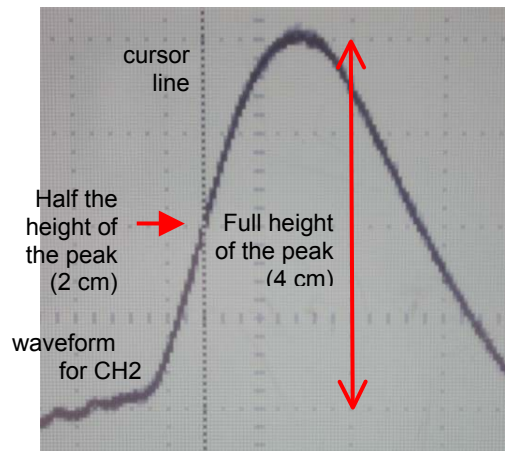


Figure II-12. Measuring the time of the pulse. Adjust the cursor to the time when the leading edge of the signal (CH2) has attained one-half of its peak. Note the dotted gridlines on the scope display.

## Exp. S1: Speed of Light (Time of Flight Method)

---

the oscilloscope display. For now you will adjust only one of them.

- Verify that the indicator at the top right of the oscilloscope screen indicates Type “TIME” and “Source CH1”. If it doesn’t, then push the menu buttons to adjust.



- Adjust the Cursor 1 knob (this is also labeled POSITION). Move the cursor horizontally until it intersects the CH2 waveform exactly where it is at  $\frac{1}{2}$  its maximum amplitude, i.e., 2 cm above its baseline. See Figure II-12.

You have now made the first half of the measurement of  $\Delta t$ . Do not touch the Cursor 1 knob until you are finished with the experiment.

- Replace the 15-cm optical fiber with the 20-m fiber.
- Note that the peak for CH2 has moved to the right on the oscilloscope display. That is due to the finite speed of light.
- Note also that the peak for CH2 has a smaller amplitude. That’s because the fiber attenuates the signal. (Plastic multi-mode fiber attenuates the signal more severely than other kinds of fiber.) To correct for this attenuation, you will need to adjust the vertical scale for CH2:
  - Press the CH2 button, then adjust the CH2 VOLTS/DIV knob until the peak of the CH2 waveform is again 4 cm above the CH2 baseline.

Now you are ready to measure the time of the peak:

- Press the CURSOR button.



- Adjust the CURSOR 2 knob (this knob is also labeled POSITION) and move the cursor line horizontally until it intersects the CH2 waveform exactly where it is at  $\frac{1}{2}$  its maximum amplitude, i.e., 2 cm above its baseline.

You have now made the second half of the measurement of  $\Delta t$ .

- Record  $\Delta t$ , as indicated on the right of the oscilloscope display as “Delta” as shown in Figure II-13. For a 20 m fiber, your result should be roughly consistent with your answer to Pre-Laboratory Question RRR.
- Calculate  $n = c / v$  for the fiber, where  $v = \Delta x / \Delta t$  is the result of your time-of-flight measurement.

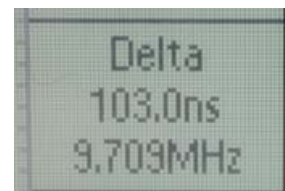


Figure II-13.  $\Delta t$  is the time between the cursors

Clean-up:

- Unplug the power supply to the Speed of Light Apparatus.
- Remove the oscilloscope cables from the Speed of Light Apparatus and from the oscilloscope inputs.
- Turn off the oscilloscope.
- Place both optical fibers back into their plastic bag.
- Tidy the workbench.

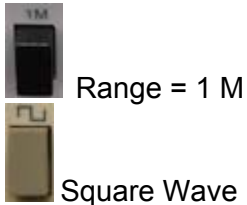
Part III: The Speed of an Electrical Pulse in a Coaxial Cable



Figure III-1. Function Generator. You will set it up to produce a 500-kHz square wave. (Instead of the BNC tee, shown here on the output, you should use a splitter to divide the signal into two cables.)

Set up the function generator

- All pushbuttons should be in the “out” position except for these two:




- Turn the “OUTPUT LEVEL” knob  to the 10 O’Clock position. This controls the amplitude of the square wave output. You will make a final adjustment later.
- Adjust the COARSE and FINE knobs for FREQUENCY so that the display reads approximately 500.0, as shown in Figure III-2. The units are kHz. Any value between 480 and 520 kHz will be ok for this experiment.
- Install a BNC-Tee connector to the function generator’s output, as shown in Figure III-3.



Figure III-2.  
Adjust the frequency to 500 kHz, using the COARSE and FINE knobs. Any value between 480 and 520 kHz is ok.



Figure III-3. Function Generator output:

Adjust the OUTPUT LEVEL initially to the 10 O'Clock position.

Set up the oscilloscope:

- Install 50 Ohm terminators on the CH1 and CH2 inputs of the oscilloscope, as shown in Figure III-4. If you have only one terminator, use it on CH2.
- Connect the oscilloscope inputs. Both of them should be connected by BNC cables to the BNC-Tee at the output of the function generator.
  - CH1 should be the shortest cable. Do not change this cable for the rest of the experiment.
  - CH2 should be one of the longer cables. You will change this cable later.



Figure III-4.  
Use a 50 Ohm terminator at the end of the BNC cables, where they are connected to the oscilloscope inputs. This avoids signal reflections at the high input impedance of the scope, yielding a cleaner waveform. (Your terminator may look different from the one shown here.)

Exp. S1: Speed of Light (Time of Flight Method)

- Adjust the scope's CH1 menu settings:



- Press the CH1 MENU button.
- Verify that all the menu selections are as shown in the left panel of Figure III-5. If they aren't, then use the menu buttons to adjust them.

- Adjust the scope's CH2 menu settings:



- Press the CH2 MENU button.
- Verify that all the menu selections are as shown in the middle panel of Figure III-5. If they aren't, then use the menu buttons to adjust them.

- Adjust the scope's trigger menu settings:

- Press the Trigger MENU button.
- Verify that all the menu selections are as shown in the right panel of Figure III-5. If they aren't, then use the menu buttons to adjust them.

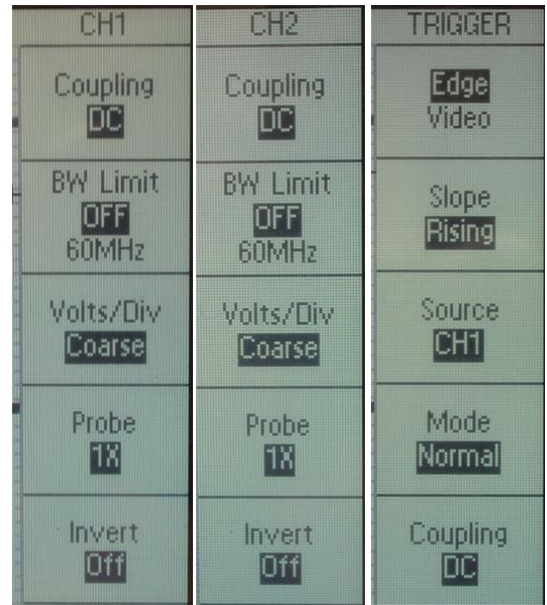




Figure III-5. Menu screens for setting up oscilloscope.

- You are finished setting the menus. Press the  button. Check that two

waveforms are displayed. If one of them is missing, press the  or  button to display the waveform for that channel.

- Adjust the scope's vertical scales:

- Examine the display of the CH1 and CH2 Volts scale, indicated at the bottom of the oscilloscope display.
- Verify that the Volts/ Div is 2.0 V for both CH1 and CH2, as shown in Figure III-6. If they aren't, then turn the CH1 or CH2 Volts/Div knobs



to adjust.

- Adjust the scope's horizontal scale:



- Examine the indicator at the bottom of the oscilloscope display, as shown in Figure III-6.

Figure III-6.

SEC/DIV setting



Exp. S1: Speed of Light (Time of Flight Method)

- Verify that the time scale is 25.0 ns per division, as shown in Figure III-6. If it isn't, then turn the SEC/DIV knob to adjust.
- Examine the "M Pos" indicator at the top-right of the oscilloscope display, as shown in Figure III-7.
- Verify that it indicates M Pos: 75.0 ns, as shown in Figure III-7. Note that this should not be -75.0 s. If necessary, adjust the HORIZONTAL POSITION knob.
- Examine the trigger threshold level at the bottom-right of the oscilloscope display, as shown in Figure III-8.
- Verify that it indicates a value somewhere in the range 200 mV to 800 mV, as shown in Figure III-8. If it isn't, then adjust the TRIGGER LEVEL knob.

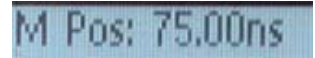


Figure III-7. Horizontal position setting.



Figure III-8. Trigger threshold level

- Adjust the vertical positions of the waveforms:

- You should see two waveforms displayed on the oscilloscope. If the waveform for CH2 is missing, press the CH1 or CH2 buttons.
- Press the CH1 MENU button.



- Turn the Position knob for CH1 until the baseline of the waveform, as indicated by the 1+ marker on the left of the scope display, is exactly 6 cm from the bottom of the display, as shown in Figure III-9.

- Press the CH2 MENU button.
- Turn the Position knob for CH2 until the baseline of the waveform, as indicated by the 2+ marker on the left of the scope display, is exactly 2 cm from the bottom of the display, as shown in Figure III-9.



Figure III-9. Adjusting the vertical position on the oscilloscope.

You should adjust the two vertical position knobs until the two markers on the left are at these positions:

1. 6 cm above the bottom
2. 2 cm above the bottom

- Your oscilloscope display should now resemble Figure III-10.

Exp. S1: Speed of Light (Time of Flight Method)

- Adjust the amplitude of the square wave so that it more nearly fills the screen, as shown in Figure III-11. Do this by turning the “OUTPUT LEVEL” of the function generator.

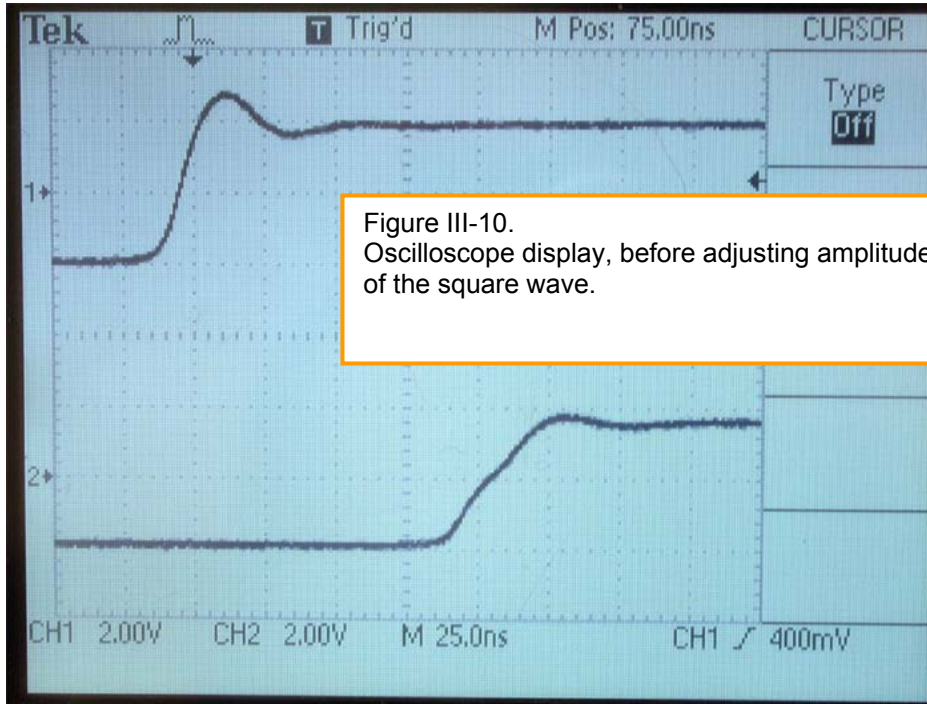


Figure III-10.  
Oscilloscope display, before adjusting amplitude of the square wave.

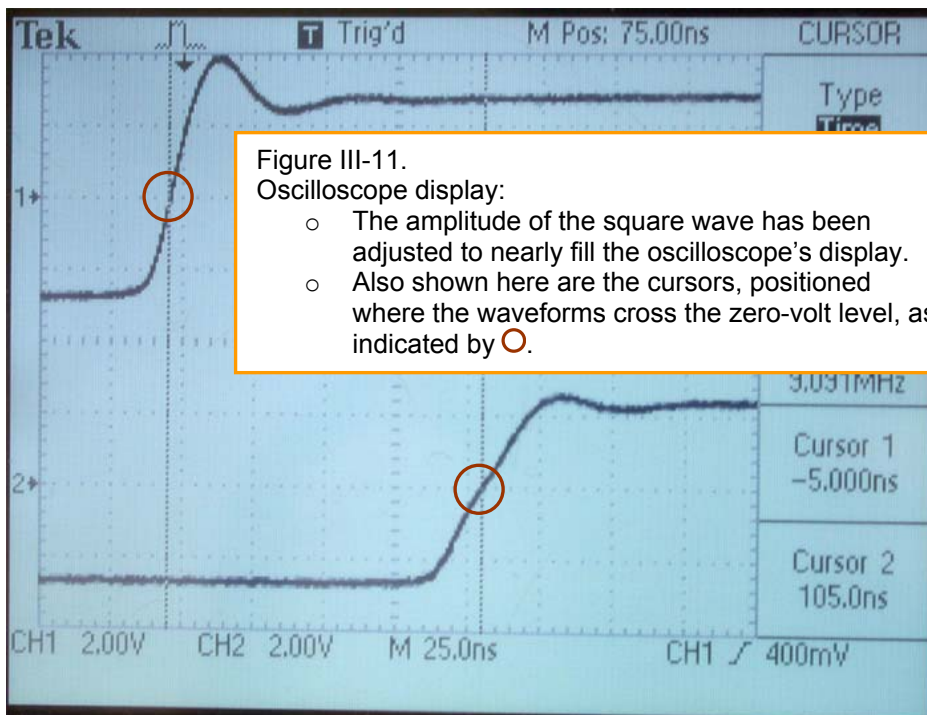


Figure III-11.  
Oscilloscope display:  
○ The amplitude of the square wave has been adjusted to nearly fill the oscilloscope's display.  
○ Also shown here are the cursors, positioned where the waveforms cross the zero-volt level, as indicated by ○.

Make the time-of-flight measurements:

You will use the oscilloscope's cursors to measure the time of the pulse. We will choose a specific point of the pulse to measure: *the point on the leading edge of the pulse where the waveform crosses the zero volt level.*

You will compare the time for a short cable on CH1 and a long cable on CH2.



- Press the oscilloscope's CURSOR button. This will produce two vertical lines on the oscilloscope display. For now you will adjust only one of them.
- Verify that the indicator at the top right of the oscilloscope screen indicators Type "TIME" and "Source CH1". If it doesn't, then push the menu buttons to adjust.



- Adjust the Cursor 1 knob (this is also labeled POSITION). Move the cursor horizontally until it is exactly where the waveform crosses zero, as indicated by the 1\* marker on the left of the display. See Figure III-11.



- Adjust the CURSOR 2 knob (this knob is also labeled POSITION) and move the cursor line horizontally until it is exactly the waveform crosses zero, as indicated by 2\* marker.

- Record  $\Delta t$ , as indicated on the right of the oscilloscope display as "Delta" as shown in Figure III-12.



Figure III-12.  $\Delta t$  is the time between the cursors

- Calculate  $\Delta x$  = the difference in length of the two cables.
- Repeat for a total of three long cables.
- Plot  $\Delta x$  vs  $\Delta t$ , including the data for all the long cables. If the origin (0,0) doesn't already appear on the plot, make it do so (in Graphical Analysis and other graphing software, this is done by double-clicking on the axis, and then applying manual rather than automatic values for the minimum value of the plot axis.)
- Fit the curve to a straight line of the form " $y = m*x$ ". The slope  $m$  is the speed of the pulse,  $v = \Delta x / \Delta t$
- Calculate the ratio  $v/c$  for the cable, is the result of your time-of-flight measurement.

## **Analysis Questions**

### Part I

- (1) Summarize all your measurements, in comparison to one another and in comparison to the accepted value of the speed of light, using a string of inequality signs. Example: my measured speed for the Volkswagen < my measured speed for the Porsche < the accepted speed of sound in air.

### Part II

- (2) Summarize your measurements, as described above.

### Part III

- (3) Summarize your measurements, as described above.