



<b>Title:</b>	<b>Measuring the Speed of Light</b>
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<b>Appropriate Level:</b>	Regents and AP Physics
<b>Abstract:</b>	Students will measure the speed of light while developing familiarity with some basic optics and electronics components such as a beam-splitter, photodiode, Fresnel lens, and oscilloscope.
<b>Special Notes:</b>	<p>*This lab write-up uses Tektronix TDS series oscilloscopes. If other oscilloscopes are used, the instructor must provide appropriate information on settings and making measurements. *Do this lab in a large space (e.g. a gymnasium or long hallway) so students can measure over a range of distances.</p> <p>*This lab <i>can</i> be done in a small room, but pay particular attention to safety with all of the laser beams in a smaller space. Make the measurements by alternately blocking the long and short beam paths so that the two pulses do not overlap on the oscilloscope.</p>
<b>Safety:</b>	Teachers should review laser safety rules with their students. <i>Set the equipment up on the floor, rather than on tables, so the laser beams are farther from eye level.</i>
<b>Time Required:</b>	If the teacher sets up the equipment, but leaves focusing, collecting, graphing, and analyzing the data to the students, then the lab can be completed in a double-period with a short time left over to compare student results.
<b>Special Notes:</b>	Created by the CNS Institute for Physics Teachers via the Nanoscale Science and Engineering Initiative under NSF Award # EEC-0117770, 0646547 and the NYS Office of Science, Technology & Academic Research under NYSTAR Contract # C020071

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### **Behavioral Objectives:**

Upon completion of this lab a student should be able to:

- Identify the parameters used in this approach to measuring the speed of light.
- Explain the role of the oscilloscope, the Fresnel lens, and the beam splitter in this lab.
- Explain the reason pulsed light is used in this lab.
- Explain the value of LASER light in this lab.

**Class Time Required:** Two class periods

**Teacher Preparation Time:** ~45 minutes

The initial equipment set-up is a little confusing, a little time-consuming, and quite ‘fussy’. The teacher should do all of the initial set-up of the scopes and the components on the base plates, and then leave the alignment, data acquisition, and analysis to the students. (See ‘Teacher’s Lab Station Set-up’)

### **Materials Needed:**

- The kit contains:
  - Iron Baseplate with height adjuster screws
  - Handi-Lens (Ultra-Optix) Fresnel Lens with magnetic mount
  - Keychain Laser
  - Beam-splitter (~ 70/30, Edmund Scientifics)
  - Fast Photodiode with Integrated Lens & external circuit (Hamamatsu model S10784)
  - Posts for the Laser, Detector, and Beam-splitter with magnets and mounts
  - Far Mirror (Plexi Mirror, American Science & Surplus ) on mount with adjustable tilt
  - Driver Circuit for laser based on a 555 chip (CMOS) that pulses light (<50 ns,MHz rep)
  - Oscilloscope (preferably digital with cursors such as Tektronix TDS series)
  - Long (at least 10m) tape measure (a fibertape with a reel can be shared by groups)

**Note: Do not touch the working surfaces of the Fresnel lens, the beam-splitter, or the far mirror. These items should only be handled by their mounts.**

**Assumed Prior Knowledge of Students:** The students should be able to solve simple motion problems. They should also be able to use their knowledge of reflection of light to align optical elements.

### **Teacher's lab station Set-up:**

- Carefully unpack the materials. Do not touch the working surfaces of the Fresnel lens, the beam-splitter, or the far mirror. These items should only be handled by their mounts.
- Connect the laser module, photodiode, Fresnel lens, and beam-splitter to magnetic posts as seen in the photographs in this lab.
- Connect the photodiode detector to channel 1 (CH 1) on the oscilloscope. Plug-in and turn on the oscilloscope.
- **Plug the 9 volt battery onto the LASER pulse generator *first*, and *then* connect the BNC 'T' connector to the laser and to the EXT TRIG input on the oscilloscope.**
- Place the laser mounting rod near the back of the baseplate and the Fresnel lens near the front of the plate (see student section figure 2). Adjust the position of the laser and the Fresnel lens so the beam goes through the small hole punched near the center of the Fresnel lens
- Place the beam-splitter between the laser and the Fresnel lens, in the path of the beam, and close to the hole in the Fresnel lens.
- Place the detector in line with the center of the lens, and just to the side of the laser beam as shown in student section figure 2. Make sure the laser beam is not blocked by the detector's post or its cable.
- Angle the beam-splitter so some of the laser light reflects back into the detector. This signal is visible as a peak on the oscilloscope. The detector is very sensitive to the position of the beam-splitter, so *the students* will have to adjust the beam splitter to obtain the largest peak possible.
- Verify that the scope settings match those in the appendix of this lab.

### **Tips for Teacher:**

- This experiment depends heavily on the set-up. Students usually have difficulty aligning the optics to obtain good signals on the scope. They frequently have trouble interpreting the signals on the oscilloscope, as well. A brief introduction to the use of an oscilloscope and/or a pre-lab demonstration of a complete set-up can remedy most of these problems.
- Students must not obstruct the laser beam with the posts or the Fresnel lens frame.
- The photodiode is very sensitive to small adjustments. A laser beam that appears to cover the diode will often result in a weak signal. Minute readjustment of the detector/lens/beam-splitter will yield a noticeably stronger signal.
- Light from the far path can be focused too much by the Fresnel lens making it difficult to place the beam on the detector. Moving the detector slightly forward or back will defocus the beam slightly and make alignment easier.
- A piece of frosted glass, scotch tape, or a white card makes a useful alignment tool. Move the card along the beam path when attempting the alignment. It is easier to see the laser beams if you can dim the room lights.

**DO NOT connect or remove the pulse generator battery while the laser is connected to it. Doing so can damage the LASER.**

- **Connect the battery to the pulse generator before connecting the generator to the LASER.**
- **Disconnect the pulse generator from the LASER before removing the pulse generator battery.**

#### Measurements and Analysis

The signals should be on the order of 50mV and separated by tens or hundreds of nanoseconds (depending on the distance from the far mirror).

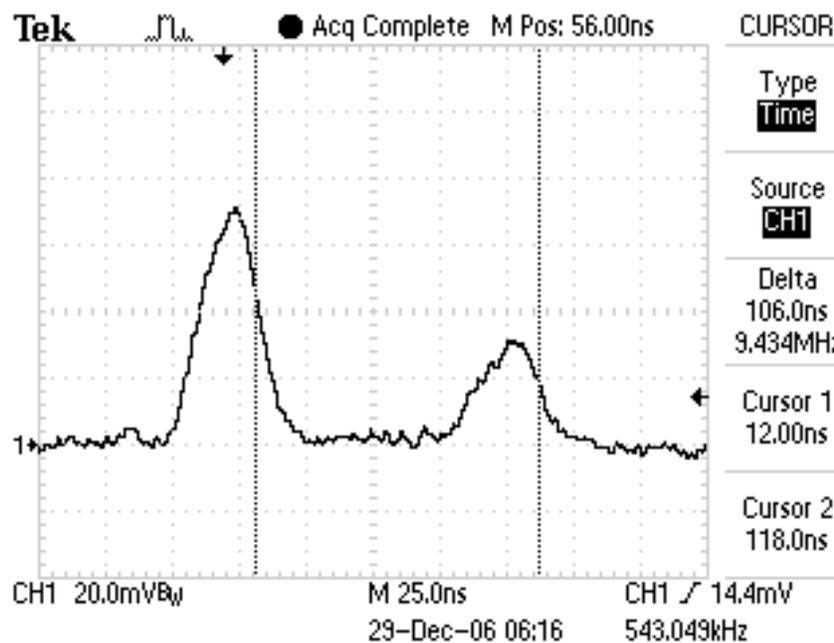


Figure T-1: Sample data for ~16 m separation.

- The far mirror to beam-splitter distance must be at least 4 meters to obtain a distinguishable pulse separation on the oscilloscope. A far mirror to beam-splitter distance greater than 8 meters is preferable. Have students measure the distance with the tape measure or meter stick carefully *but quickly*. The uncertainty in the measurement of  $\Delta t$  of the signals will dominate the ~2% error expected from measuring  $\Delta L$  by hand.
- Questions on the  $\Delta L$  measurement are common. The two paths of light become distinct at the beam-splitter. The pulse taking the short path goes directly from the beam-splitter to the detector and arrives first. The pulse taking the long path must also go to the far mirror and then back to the detector.
  - Method #1: Measure the long path and the short path distances and subtract to obtain  $\Delta L$ .

- Method #2 (Easier): The distances between the laser and the beam-splitter and between the beam-splitter and the detector are the same for both beam paths, and 'drop out' of the  $\Delta L$  calculation. Therefore the round trip distance from the beam-splitter to the far mirror is  $\Delta L$ .

**Oscilloscope 'tricks'** (not all can be done at once)

- This whole experiment happens in less than 1 microsecond, so the signal from the fast photo detector is connected directly to the CH 1 input BNC jack on a very fast scope. The experiment can be done with just this one connection to the scope, but it is better to have a *trigger signal* to reset the time axis to zero when the system should expect the data (laser pulse) to arrive. The electronic pulse generator which drives the laser can provide just such a trigger signal. A BNC 'T' connector on the pulse generator sends the signal to the EXT TRIG (external trigger) input on the scope and to the laser at the same time.
- The oscilloscope settings found in Appendix A work well for this experiment. The Tektronix TDS series scope provided by the CIPT, should come up with these pre-set. If they are not, try the 'SAVE/RECALL' button near the upper left corner of the front controls. Use the soft buttons along the side of the display to 'Recall Settings', '1' and then select 'Recall'. If that doesn't work, the settings will have to be entered manually.
- Use the 'store' function of the oscilloscope to freeze the screen, making it easier to place the cursors, ignoring some of the noise. Use the halfway point of the falling-off side of the peaks instead of the peaks themselves when measuring  $\Delta t$  to obtain more consistent results.
- One can set the oscilloscope to average several scans to reduce noise.
- Perform a sequence of measurements on single scans.

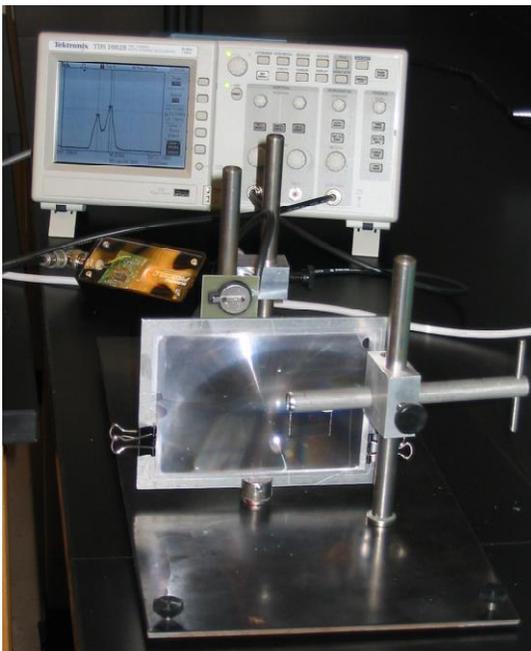
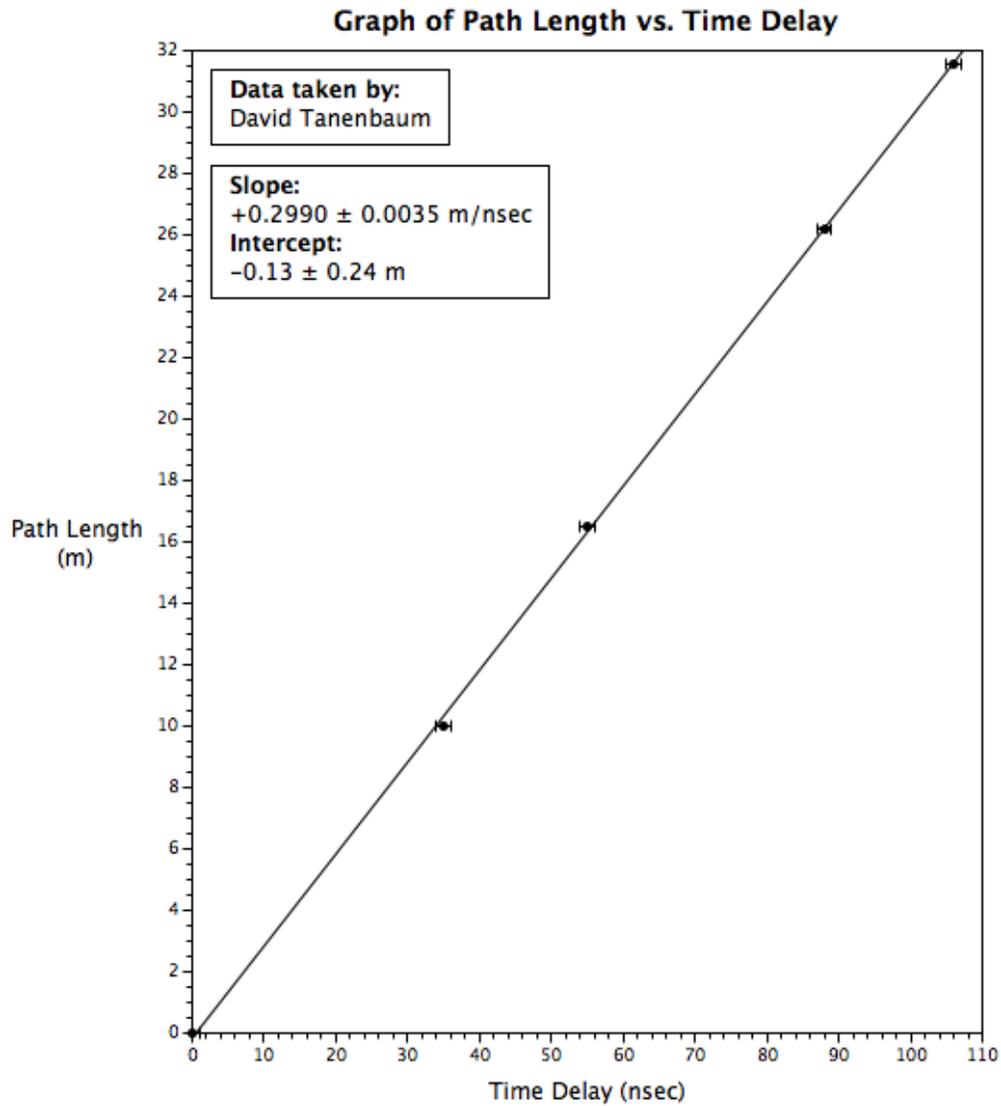


Figure T-2: The oscilloscope and pulse generator w/ the beam-splitter, Fresnel lens, photo detector and laser mounted on the baseplate. (Note: The system works better with the beam-splitter on the other side of the Fresnel lens as described in the lab.)



Data for this Plot:

<u>Time Delay (nsec)</u>	<u>Path Length (m)</u>
35 ± 1	10.00 ± 0.02
106 ± 1	31.56 ± 0.02
55 ± 1	16.50 ± 0.02
88 ± 1	26.20 ± 0.02
0 ± 1	0.00 ± 0.02

Note: Without including the origin, the values are:

Slope =  $0.302 \pm 0.005$  m/nsec  
Intercept =  $-0.38 \pm 0.38$  m

Figure T-3: More Sample Results

## Equipment



Photo ID	Quantity	Item
1	1	Handi-Lens (Ultra-Optix) Fresnel Lens with metal frame holder, magnetic mount and binder clips
2	1	Beam-splitter with magnetic post
3	1	Far mirror on adjustable mount
4	1	Fast Photodiode with Integrated Lens and external circuit with magnetic post and BNC connector
5	1	Pulse generator and mounted laser with magnetic post and BNC connector
6	1	Iron base plate with adjustable screws
Not shown	1	Oscilloscope
Not shown	1	10m tape measure on reel

# MEASURING THE SPEED OF LIGHT

## Pre-Lab Reading (pages 1 & 2)

### Introduction

As you know, the speed of light is very, very fast and nothing can go faster than light goes in a vacuum. People have been measuring the speed of light, or at least trying to, since Galileo's time in the early 1600's. Until very recently, the methods have involved '*time-of-flight*'. These are methods that use the distance traveled divided by the time it takes to travel that distance. Since light travels so fast, one must either use extremely large measurable distances or find a way to measure extremely short time intervals (or both!). You will determine the speed of light in this lab by measuring manageable distances right in the lab room, and measuring extremely short time intervals using an oscilloscope.

The Experimental Set-Up (See Figures 1 and 2 below):

In this *time of flight* experiment, a single pulsed laser beam is split into two pulsed beams by a partially reflecting mirror called a beam splitter. Part of the light passes through the mirror, and the rest is reflected off the mirror. The reflected part of the beam travels a very short distance of a few centimeters to a photo detector, while the transmitted part of the beam travels a much longer path of several meters before returning to the same detector. The pulse traveling the short path will arrive at the detector first, and the pulse that travels the longer path will arrive a bit later, since it has to travel farther. By measuring the extra time taken for the pulse of light to go the longer distance, and measuring the extra path length that this pulse must travel, you can determine the speed of the light. The extra distance is easy to measure with a tape measure or meter stick, but the time between the arrival of the short-path and long-path light pulses is on the order of nanoseconds (billionths of a second). The measurement of the ultra-short time intervals in this lab requires use of a high-speed photo detector and a digital oscilloscope, as you will see.

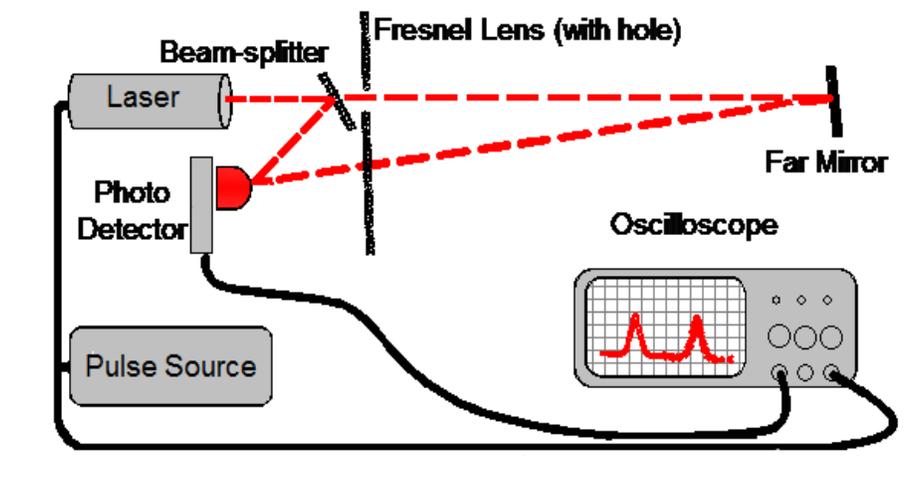
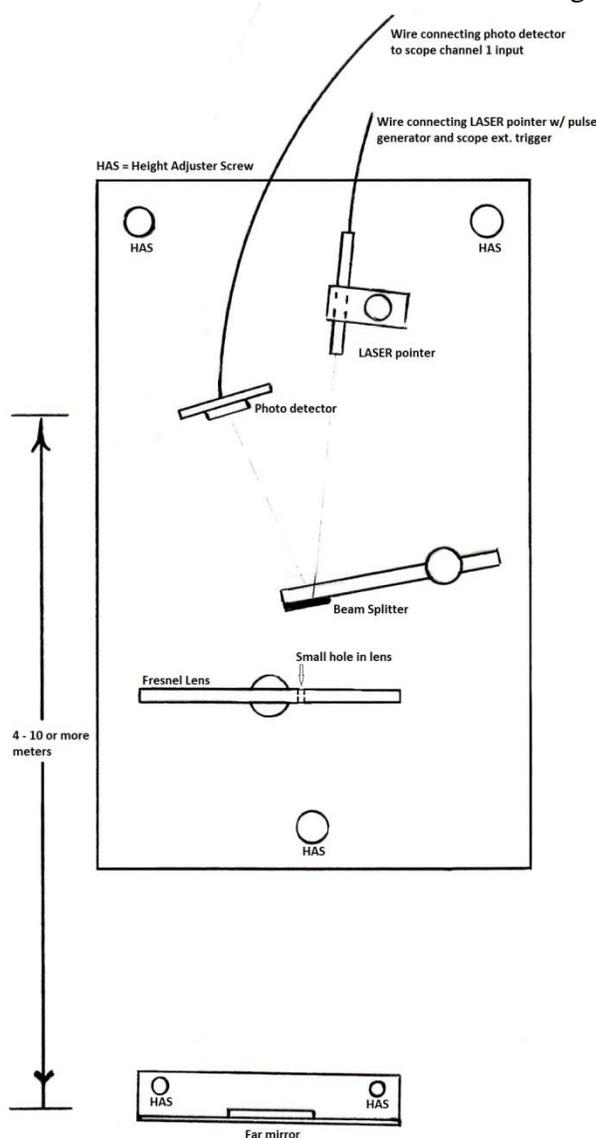


Figure 1



The laser, beam-splitter, Fresnel lens, and photo detector are all mounted on a large iron baseplate with magnetic bases as shown in the top view in Figure 2. This keeps the short path parts aligned with each other. The baseplate, with screws to adjust its tilt, is set on the floor and adjusted to aim the laser at the far mirror placed 4-10 meters away. The far mirror is then adjusted to reflect the laser beam back and into the detector. Careful alignment of the parts provides a strong signal on both light paths, and strong signals make the analysis much easier and results superior.

***Warning!*** Do not touch the surfaces of the Fresnel lens, the beam-splitter, or the far mirror. These items can all be handled by their mounts.

***Warning!*** Never look into a LASER beam path. Even laser pointers can cause eye damage. We will minimize the risk that an errant laser beam could hit anyone in the eye by doing the experiment near the floor. Remember that reflected laser light is also a risk!

The oscilloscope (or ‘scope’ among friends) is one of the most important tools in physics laboratories. Its main purpose is to display graphs of voltage as a function of time. If a voltage changes *very* slowly, you can measure it with a voltmeter at regular time intervals (say every 5 seconds) and draw a graph of the data. But what if the voltage changes measurably in milliseconds, microseconds, or even nanoseconds? Oscilloscopes are important because they measure and graph voltages in otherwise immeasurable time scales like those in this lab.

Like a cell phone, a scope has one main purpose which is rather simple; but it has plenty of buttons and menu options that tweak the way it works and make it much more useful (and complex). For example, most scopes can display 2 independent channels (voltages) on the vertical axis versus the time on the horizontal axis. You can learn about the ‘tweaks’ later.

**Part I – Aligning the System:** Your teacher has assembled the equipment for this lab, and you must now align the components and collect your data.

- Turn on the oscilloscope.
- **Plug the 9 volt battery onto the LASER pulse generator *first*, and *then*** connect the BNC “T” to the laser and to the EXT TRIG input on the oscilloscope. To attach a BNC connector, push it straight onto the scope connector and then turn its ring clockwise. You might feel a ‘click’ when it locks into place.
- Adjust the position of the laser and the Fresnel lens so the beam goes through the small hole punched near the center of the Fresnel lens
- The detector should be in line with the center of the Fresnel lens, and just to the side of the laser beam as shown in figure 2. Make sure the laser beam is not blocked by the detector’s post or cable.
- Angle the beam-splitter so some of the laser light reflects back into the detector. This signal is visible as a peak on the oscilloscope. The detector is very sensitive to the position of the beam-splitter, so adjust the beam splitter to obtain the largest peak possible.
- Adjust the leveling feet on the baseplate to get the transmitted portion of the laser beam, the part that goes through the beam-splitter and continues through the hole in the Fresnel lens, to be as close to parallel to the floor as possible and to hit the far mirror. (Hint: Look for the laser beam hitting the wall on the opposite side of the room or try interrupting the beam with a piece of paper and walking the path keeping the beam on the paper.)  
**CAUTION: Make sure the laser light is not reflecting to anyone’s eye level, including your own!**
- With the far mirror on the floor in the path of the laser beam and at the desired distance, adjust it to return the beam to roughly the center of the Fresnel lens. Adjust the far mirror horizontally by pivoting the entire far mirror mount from side to side. Adjust it vertically by turning the leveling screws. While the same technique of tracking the beam with a piece of paper works on the return trip, be careful not to block the *outgoing* beam with the paper. Have a partner across the room direct this process to get as much of the beam as possible to hit the Fresnel lens. Spend the time necessary to obtain good alignment and the resulting strong signal (peak) on the scope.
- Have one person hold the base plate *absolutely* still. Gently adjust the position of the detector, without moving any of the other optics, until the Fresnel lens focuses the far beam onto the detector. The signal on the oscilloscope from the near beam will usually disappear, but the signal from the far beam should appear.
  - Adjust the detector up or down by loosening the thumb screw that clamps to the post.
  - Adjust the detector side to side by gently rocking or twisting the magnetic post while maintaining contact with the baseplate.
  - Monitor how the Fresnel lens refocuses the diffuse laser beam with a file card in the light path. Place the detector where the beam is most tightly focused. The more light entering the detector, the stronger the signal; *but* the smaller the beam spot is, the more carefully the detector must be positioned. Position the detector to maximize the

oscilloscope signal from the long path. It should be almost as strong as the short path signal was.

- With the long path signal displayed on the oscilloscope, a slight readjustment of the beam-splitter will return the short path beam to the detector and cause it to reappear on the scope as well.
- With both peaks displayed on the oscilloscope, separated slightly on the horizontal (time) axis, block each beam individually to identify the peaks.

## **Part II – Collecting the Data**

Now that the equipment is set-up and aligned (congratulations), you can make the necessary measurements very quickly. The oscilloscope will display the time ( $\Delta t$ ) it takes the pulse of light to travel the distance to the mirror and back. The distance ( $\Delta L$ ) can be measured with a tape measure or meter stick.

1. The difference in path length between the short and long paths is simply the round trip distance from the beam splitter to the far mirror. Why is it not necessary to include the distance between the laser and the beam-splitter and the distance between the beam-splitter and the detector?
  - Measure the distance from the beam-splitter to the far mirror with a tape measure. Double this measurement to obtain the round trip distance. **Record this as ' $\Delta L$ ' in the data table below.**

Use the digital oscilloscope to measure the time.

- Adjust the CH 1 VOLTS/DIV to get the peaks to fill most of the height of the display area.
- Adjust the SEC/DIV to get the two peaks to fill most of the width of the display area.
- Tektronix TDS series scopes have a cursor function to make reading data from the scope easier.
  - Press the CURSOR menu button
  - Set the Type to 'Time' and the Source to 'CH1' using the softkeys next to the display screen.
  - Move the vertical lines to mark the midpoints on the downward slopes of the two peaks by pressing the softkey for 'Cursor 1' or 'Cursor 2' and turning the knob at the top center of the scope with the green LED lit near it. The position of each cursor is displayed next to a lower softkey on the screen. The time between the cursor positions is labeled 'delta' and appears next to the middle softkey as in Figure 3. **Record this number under ' $\Delta t$ ' in the data table below.**
- If the scope does not have cursors, estimate the time delay by counting the divisions between the peaks and multiplying by the SEC/DIV number on the horizontal (time) axis.

2. Calculate the speed of light ( $c$ ) using  $c = \frac{\Delta L}{\Delta t}$  Show your work. Find percent error.

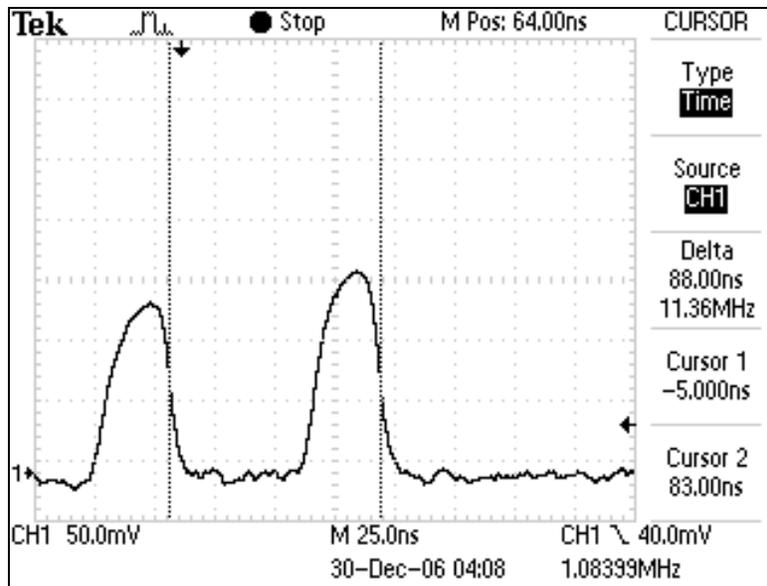


Figure 3: Sample Oscilloscope Screen with far mirror 13.1 meters from beam-splitter. (Note the positions of the vertical cursors and the display of their positions on the screen.)

*Disconnect the pulse generator from the LASER and the scope before removing the pulse generator battery.*

**Part III – Group Results**

- Pool your results with those of the other lab groups in the table below in order to examine the effect of varying distances of the far mirror.

Team #	$\Delta L$ (meters)	$\Delta t$ (seconds)	Speed of Light (c) (meters/second)
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

- Graph  $\Delta L$  vs.  $\Delta t$
- Draw in the best fit line, but force it to include the origin.
- Find the slope of the best fit line on the graph, including units.

3. Slope = \_\_\_\_\_

4. Why is the origin included in the best-fit line on the graph even though it is not actually a measured data point?

5. What is the meaning of the slope of this graph?

6. What was the class group result for the speed of light?

$c =$  \_\_\_\_\_

7. How did you determine which light pulse displayed on the oscilloscope was from the short path and which one was from the long path?

## APPENDIX A: Typical Oscilloscope Settings

PARAMETER	VALUE	LOCATION ON FRONT PANEL
CH 1 Sensitivity	10 mV/div	VOLTS/DIV Knob above CH 1 input BNC jack
CH 1 Coupling	DC	Soft button on CH 1 Menu
CH 1 BW limit	Off	Soft button on CH 1 Menu
CH 1 Probe	1 X	Soft button on CH 1 Menu
CH1 Invert	Off	Soft button on CH 1 Menu
Horizontal Axis	25 nsec/div	SEC/DIV Knob above EXT TRIG input BNC jack
Trigger Type	Edge	Soft button on TRIGGER Menu
Trigger Source	Ext	Soft button on TRIGGER Menu
Trigger Slope	Falling	Soft button on TRIGGER Menu
Trigger Mode	Normal	Soft button on TRIGGER Menu
Trigger Coupling	DC	Soft button on TRIGGER Menu
Trigger Level	~ -500 mV	TRIGGER LEVEL small knob in upper right corner
Middle Position	100 nsec	HORIZONTAL POSITION small knob 2 <sup>nd</sup> from right
Averaging	Average: 4	Soft buttons on ACQUIRE Menu (top center button)

