Measuring the Speed of Light

Lab Manual by:
Eric Mueller
Dan Passmore

Introduction

When you want to measure the speed of something, how do you do it? Generally, you measure off a specific distance, get out a stopwatch, and clock it. You divide the distance by the time, and you know that the car was traveling at around 20 mph. What about in really fast sports? You can't trust time differences of $1/100^{th}$ of a second to a human finger… We use machines to trigger the clock in that case. Computers run at far greater speeds, and the time it takes one of them to trip a clock is far less that .01 s. But we want to measure the speed of light. Nearly by definition, there is nothing fast enough to trip a clock on light. At laboratory distances, an error of .0001 s throws off your result by a factor of 1000.

How to get around this? Our basic problem is that we don't have anything that moves fast enough to respond to the light. But we do have things that move very fast… we can get objects *spinning* VERY rapidly, into the kHz range. This is the basis for the rotating mirror experiment.

Overview

4) Laser
B) Rotating Mirror
C) Large Lens
D) Plane Mirror
E) Beam Splitter
F) Photodiode + Oscilloscope
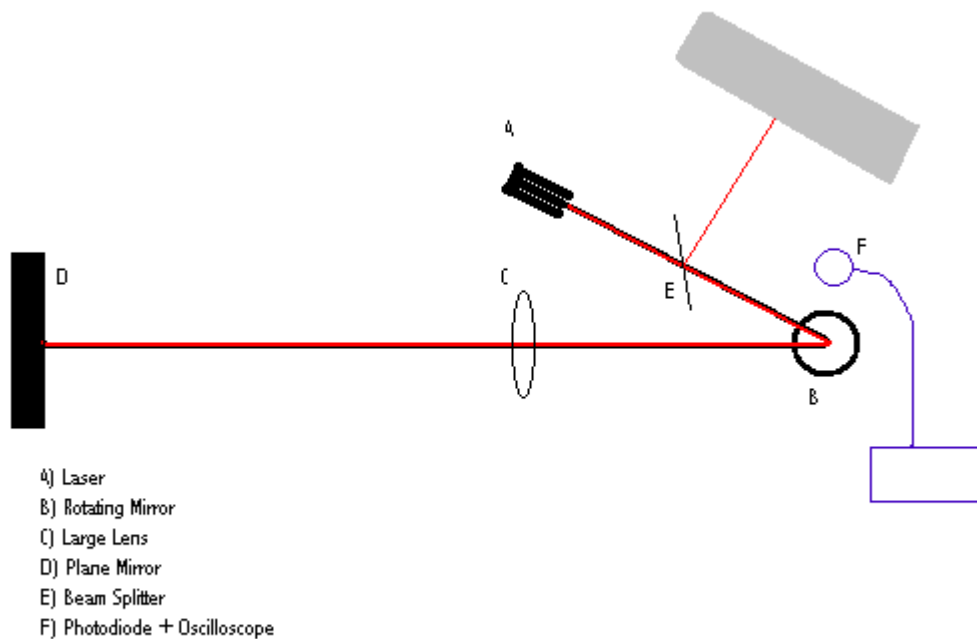
Let's follow a photon through the experiment. First, it leaves the laser, passing through the beam-splitter. (The ones that reflect off of the splitter going this direction have no effect on the experiment) Then it hits the rotating mirror, reflecting toward some part of the lens. (Only part of the light each rotation of the mirror does this. The part that doesn't reflect toward the lens – that's most of it—also has no effect) After hitting the lens, which is located one focal length away from the rotating mirror, the ray is oriented perpendicularly to the plane mirror on the far wall, because the point of origin (the rotating mirror) is like a point source, and rays from a point source at the focal point exit parallel.

After the photon hits the plane mirror and is reflected back, exactly follows its own path back through the lens, and comes back to the rotating mirror exactly from where it left. In that amount of time, the mirror has spun a certain distance (not a very large distance. A few degrees, at most), and the ray will not exit precisely along the path that it entered the mirror on. The ray will reflect off of the splitter, and show up on the wall. When the mirror is not spinning, and is simply oriented to reflect ALL of the light toward the lens, the light follows its own path here also, and gives us the location it ought to be at. Since the mirror is spinning, the beam shifts a bit to the right. By measuring the size of that shift, and knowing the speed at which the mirror is spinning, we can calculate how far the mirror travels in the time the light takes to go to the far end of the hallway and back, and therefore how long it took the light to do so.

The Pieces

If you'll refer to the diagram on the previous page, I have labeled all of the parts. Here follows a description and explanation of each of them, and the part they play in our experiment.

A) The laser:

This part's fairly obvious. In the original experiment, Michelson used a lightbulb and a pinhole, but a laser is FAR superior for this type of experiment. Be glad you were born after they were. (The coherence length isn't of great significance in this experiment, and surprisingly, the divergence doesn't impact results very much either. You'll see why later. Pick the brightest one you can easily use—intensity is the important thing here.

B) Rotating mirror:

If you read the part above, you'll already know kind of what this is for. We need one that spins in the kHz range (in our run, 1.26 kHz got reasonable results, but the faster, the better.) Check if the mirror is double-sided—it's a bonus, but if you don't notice it, your results will be off by a factor of 2. You don't have to know actual speed of your rotation yet, we'll measure that later.

C) Large lens:

Strictly speaking, this part isn't necessary. If you had a VERY powerful laser, and a tiny divergence, the experiment would work without this lens. You don't. This lens has two important roles to play. First, it causes beams that hit it to retrace their path back to the rotating mirror—if it weren't present, these beams would hit the far mirror, but they wouldn't generally be perpendicular to it, so they wouldn't ever come back to the rotating mirror. (except a few. Those ones alone don't provide enough intensity to see the results.) The second role is that it refocuses the beam. Since the light exits the lens parallel, reflects, and reenters, you might think that the distance from the lens to the plane mirror is arbitrary. Because this distance does not affect the results, we select it to bring the beam back to a point at the measuring surface. Without this effect, a normal optics-lab laser's beam would be several centimeters wide, and the distance we are trying to measure is actually only a centimeter or so across. Ours had a focal length of 5 m, and was 11 cm across.

D) The plane mirror:

Can't get simpler than this, folks. This mirror reflects the rays back toward the rotating mirror. It needs to have good adjustment knobs, because you need to steer the beam back to the rotating mirror with them. At this range, it's pretty difficult.

E) Beam splitter:

This part is only for convenience. It's easier to take measurements on the wall than on the front surface of the laser casing. It's important that the beam reflecting off of this at the end be nearly perpendicular to the wall. A large one is easier to use in this experiment – we used a one-inch, and had to be careful about keeping beams from touching the edges of the splitter.

F) Photodiode and Oscilloscope:

        In the original experiment, Michelson used a tuning fork to tune the motor to a specific frequency. We again have better tools available. We set up a photodiode for the reflected laser to spin across while the equipment is running, and hooked it up to an oscilloscope. We observed a regular pattern, determined the frequency of the pattern, and thus learned the angular speed at which the mirror was spinning. Our answer was wrong. Remember to check and see if your rotating mirror has two sides or one side – here is where it matters. A two-sided mirror is only spinning half as fast as a one-sided mirror with the same oscilloscope plot. Don't make one reading here and assume the speed of the rotating mirror is constant. Take this measurement every time you run the experiment.

In our version of the experiment, the rotating mirror, laser, and beam splitter are all mounted together on a mobile optical bench. The plane mirror and the lens are both on separate stands, to be placed further down the hall.

Distances

S is the distance by
which the point of
light on the wall
moves.

z

b   f
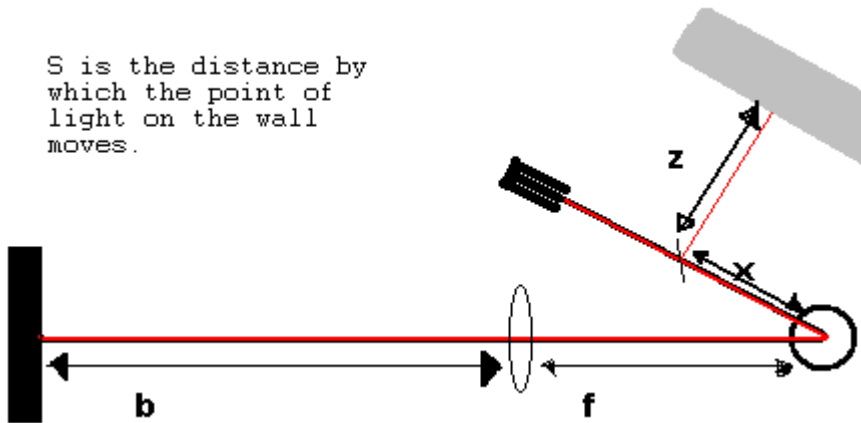
The distance f is the focal length of your lens: 5-10 meters, preferably.
X can also be chosen by the experimenter; we used a distance of around 60 cm.
Z should be chosen so that the distance from the wall to the splitter is close to the
        distance from the laser aperture to the splitter. Lots of leeway here – ours is
        almost double the distance.
With these distances chosen (largely by our equipment) **b** may be calculated:

$$f^{-1} = (z + x + f)^{-1} + b^{-1}$$

If **b** turns out to be too long or too short for the space in which you are working, adjust z,
and x if necessary.

Setting up – Preparation and Calibration

Setting this experiment is not difficult, unless your adjustment knobs are not fine enough. First set up the laser, beam splitter, and rotating mirror. The laser needs to hit the center of the mirror, and pass through the middle of the splitter. Rotate the mirror so that the laser light is reflected down the hallway (if this experiment is in a place where people might go, put up warning signs at all entrances to the hallway, asking people to let you know they are entering, so you can turn off the laser) Now go set up the plane mirror and the lens at the appropriate distances. Though the method of measuring these distances is unimportant, this part is easier if you have a floor made of regular square tiles. Try to orient the lens perpendicular to the beam as well as you can by eye. It won't be adjusted later.

The beam should be shining through the center of the lens and hitting the center of the plane mirror. Now adjust the plane mirror so that the beam goes back through the lens in the same place—This part is easiest if you have a partner, as you will not be able to adjust and check the location of the beam at the same time. (too dim and far away) Once you have the beam shining through the same spot on the lens comes the delicate part. We need to continue adjusting until it actually hits the rotating mirror again. You won't be able to see this at all – the way to check if it is hitting is by looking at the wall. If the return beam is hitting the currently-not-rotating mirror, then there will be a spot in the measuring area, as the returning beam hits the splitter. Otherwise, there is not light traveling in that *direction* hitting the splitter, and no spot will appear on that side of the experiment. Once you have this lined up, be careful. If you bump anything connected to the laser, a mirror, or the lens, you get to do all this over again. (another reason to warn people not to enter the hallway). Mark the current location of the spot.

Now we set up the diode. Mount it on something so that it is level with the rotating mirror, and turn on the rotating mirror, slowly. The oscilloscope should get a spike each time the beam crosses the diode. *Slowly* turn the speed up, until you shouldn't turn it up any further (ask your lab instructor how much current you should allow this machine before you run it). Now use the oscilloscope to measure the frequency of the wave it is showing (If you need help operating the oscilloscope, ask for it. Sometimes these are NOT straightforward. But playing around with the oscilloscope is pretty safe.) This frequency is the speed of the rotating mirror in rotations per second. Or double that speed if the mirror is double-sided. (Think about why) If the speed is below 800 Hz, your results won't be very good.

Performing the experiment

Check that all the things you calibrated earlier still are in place. Turn the motor on at a low speed, and see that there is a flickering dot on the wall (this is at essentially the same location as it was when the motor was not on, and you were adjusting the mirror). If there is no flickering dot, recalibrate. Slowly turn the motor all the way up. Record the frequency of the wave on the oscilloscope – was it different from the value recorded earlier? Now measure the distance by which the dot has moved from when the motor was moving slowly. This distance is very small – ours was in the range of several millimeters. Generally, the faster your motor, and the greater the distance **b**+**f** you use, the larger the measured distance S will be.

Calculating results
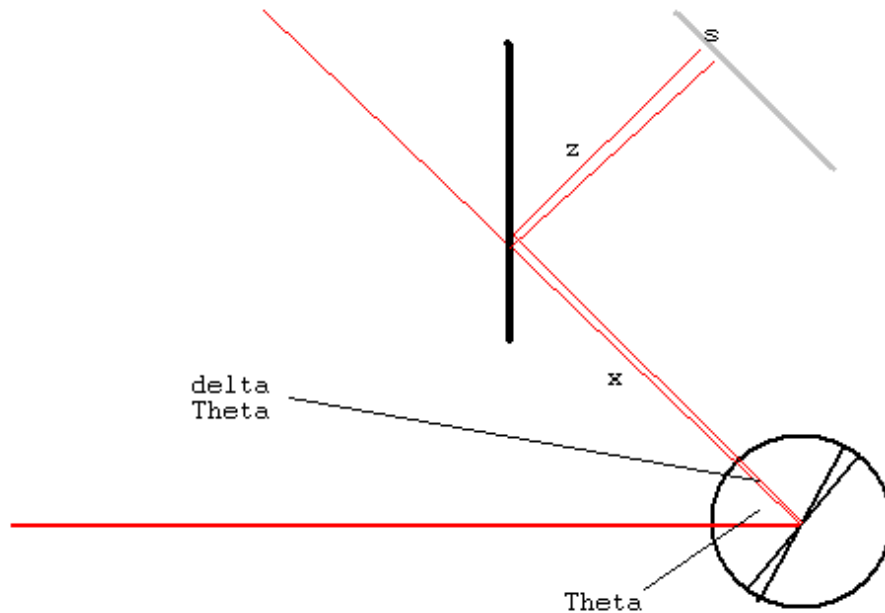
The important triangle effectively has two right angles- if we unfold the triangle, we have:
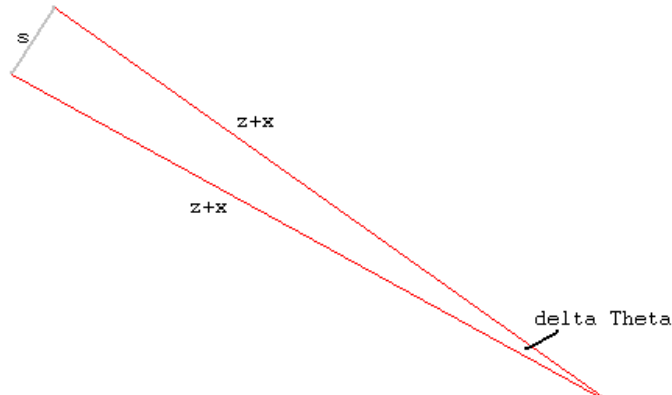
So $\Delta \Theta = \sin(\Delta \Theta) = s / (z+x)$.　　　[Small angle approximation]

$F*2\pi = \omega = \Delta \Theta / \Delta t$, so　　　[Definition of ω]

$\Delta t = \Delta \Theta / \omega = (s/(z+x)) / (f * 2\pi) = s / ((z+x)*f*2\pi)$
　　　　　　　　　　[substitution]

Δx = the distance the light traveled in the time measured,
 and $\Delta x = 2 * (f+b)$　　　[there and back]

Altogether, $\Delta x/ \Delta t = (2*(f+b)*(z+x)*f*2\pi) / s = C$.
　　　　　　　[formula for average speed. We assume that
　　　　　　　　　　C is constant…]