Union College Winter 2022

**Phy122 Lab 2**

## The Michelson Interferometer: Calibration, Planning for Sensitive Experiments, and Obtaining Null Results

The experimental evidence that both established the law of physics that the speed of light in vacuum is always the same value in all inertial reference frames and that dispelled the concept of the ether was the Michelson-Morley experiment. The device used is now referred to as a Michelson interferometer, which provides a sensitive measurement of either the wavelength of light or of small differences in distances.

Michelson and Morley had set out to use their interferometer to determine the motion of the Earth relative to the ether, but, instead, they continually obtained null results (i.e., no effect measured). In order for a null result to be significant and be considered sufficient to overturn scientific beliefs, the experimenters must perform very careful error analysis and have very strong confidence in their assessment of their uncertainties. Michelson and Morley’s null results were significant because their expected quantitative result was significantly larger than their uncertainty, and their error analysis of their experiment was done carefully enough that their uncertainty was accepted by the physics community as well done.

There have been many null-result experiments that have had significant impacts on the advancement of physics and science. Knowing how to perform sufficiently careful error analysis has proven to be a valuable skill in experimental physics.

For a successful scientific research project, the first stage should entail careful planning. To obtain funding for a project, for example the researcher needs to find an instrument that is sensitive enough for a successful detection and then show the ‘technical feasibility’ calculation in a proposal to be submitted to the granting agency. This is an especially helpful calculation for a null result to be significant -- the researcher can then show that the planned experiment is sensitive enough that a null result will necessarily disprove a theory (as was the case with Michelson and Morley).

In this lab you will become familiar with the Michelson interferometer, calibrate the instrument and estimate the uncertainty in the measurement of the difference in travel time of the two beams. Imagining you were considering doing the Michelson-Morley experiment in the 1880s, using your uncertainty as the minimum detectable time difference, you will compare with the minimum expected time difference and conclude whether the experiment could be successful.

# How the Interferometer Works

A beam of light can be modeled as a wave of oscillating electric and magnetic fields. When two or more beams of light meet in space, these fields add according to the principle of superposition. That is, at each point in space, the electric and magnetic fields are determined as the vector sum of the fields of the separate beams.

The apparent intensity of the light is proportional to the square of the electric field, so where the sum of the electric fields is large, the light will appear intense. However, the oscillations of visible light are far faster than the human eye can detect. The human eye averages the oscillations and so perceives a uniform intensity of light.

If two beams of light originate from the same source, the frequencies and phases of the electric field oscillations in the two beams are related. At one point in space the light from the beams may be continually in phase. In this case, the combined field will always be a maximum and a bright spot will be seen. The waves “constructively interfere.” At another point the light from the beams may be continually out of phase by exactly a half-cycle (or  radians) so that the electric fields cancel and a minimum, or dark spot, will be seen. This is “complete destructive interference.” Thomas Young’s 1803 two-slit experiment which yielded an interference pattern on the screen opposite the slits was considered important evidence for the wave nature of light.

In 1881, 78 years after Young introduced his two-slit experiment, A.A. Michelson designed and built an interferometer using a similar principle. Originally built to test for the existence of the ether, Michelson’s interferometer has become a widely used instrument for measuring the wavelength of light, for using the wavelength of a known light source to measure extremely small distances, and for investigating optical media.

Viewing screen

lens

movable mirror (M1)

Laser

Beam splitter

adjustable mirror (M2)

Figure 1: Michelson Interferometer

Figure 1 shows a schematic of a Michelson interferometer. The beam of light from the laser strikes the beam splitter, which reflects 50% of the incident light and transmits the other 50%. The incident beam is therefore split into two beams; one is transmitted toward the movable mirror (M1), and the other is reflected toward the fixed adjustable mirror (M2). Both mirrors reflect the light directly back toward the beam splitter. Half of the light from M1 is reflected from the beam splitter to the viewing screen and half the light from M2 is transmitted through the beam splitter to the viewing screen. In this way the original beam of light is split, and portions of the resulting beams are brought back together. Since the beams are from the same source, their phases are highly correlated. If the distances the two beams travel are equal, the beams arrive in phase and a bright spot is seen on the screen. If the difference in the distances is exactly one half of a wavelength then the beams arrive exactly radians out of phase and so their electric fields cancel.

Figure 2: Interferometer interference fringes

When a lens is placed between the laser source and the beam splitter, the light ray spreads out. For light that hits the screen at positions offset from the center, the two paths will have slightly different distances and so there will be a dark circle around the center, and then a bright circle. An interference pattern of dark and bright rings, or “**fringes**,” is seen on the viewing screen (figure 2).

By moving M1, the path length of one of the beams can be varied. Since the beam traverses the path between M1 and the beam splitter twice, moving M1 a distance = 1/4 wavelength nearer the beam splitter will reduce the optical path of that beam by 1/2 wavelength. The interference pattern will change; the radii of the maxima will be reduced so they now occupy the position of the former minima. If M1 is moved an additional 1/4 wavelength closer to the beam splitter, the radii of the maxima will again be reduced so maxima and minima trade positions, but this new arrangement will be indistinguishable from the original pattern. Hence, each time the mirror is moved a distance of */2 (*where ** is the wavelength of the light), another fringe has moved into the center. If the mirror is moved a distance

*dm*= *m /2*, (1)

then *m* fringes will pass through the center*.*

**Michelson and Morley’s test of the motion of the Earth relative to the ether**. As discussed in class (and in your text), at the time of Michelson and Morley’s experiment, the general belief about light waves and the speed of light was that there was a medium space, called the ether, which propagated light waves and c was the speed of light relative to the ether. We now know that there is no ether and the speed of light is a constant for all reference frames. In this lab, though, you are to reproduce the Michelson-Morley experiment. As derived in class, if the earth moves relative to the ether frame with velocity *v* to the right in Figure 1, and if *c* is the speed of light only relative to the ether frame, the difference in arrive time of the beams will be

$∆t\_{arrival}=\frac{2L}{c}\frac{1}{\sqrt{1-\frac{v^{2}}{c^{2}}}}\left[\frac{1}{\sqrt{1-\frac{v^{2}}{c^{2}}}}-1\right]$. (2)

# Procedure

1. Check to be sure you see a circular pattern of fringes on the screen. If not, then the laser alignment probably needs adjusting – call the instructor over.

2. Note the micrometer knob and notice that as you turn the knob a small amount the fringe pattern changes. When you turn this knob, you move mirror M1. However, the amount you turn the knob according to its markings and the distance that the mirrors are not exactly. Your first task is to CALIBRATE your instrument. In this case, you need to know how many ms the mirror moves for every division on the micrometer knob. Note that markings on the rotating knob are each 0.01 of a division on the non-rotating rod.

3. Start by moving the micrometer to a mid-range reading (i.e. not at either end of the rod). In this position, the relationship between the micrometer reading and the mirror movement is most nearly linear.

4. Turn the micrometer knob one full turn counterclockwise. Continue turning counterclockwise until the zero on the rotating knob is aligned with the index mark.

 NOTE: When you reverse the direction in which you turn the micrometer knob, there is a small amount of give before the mirror begins to move. This is called mechanical backlash, and is present in all mechanical systems involving reversals in direction of movement. By beginning with a full counterclockwise turn, and then turning only counterclockwise when counting fringes, you can eliminate errors due to backlash.

5. CALIBRATION: As one lab partner turns the micrometer dial in very small amounts the other partner watches the fringe pattern. Turn the knob until the pattern changes by 10 fringes. By how much has the reading on the micrometer changed? Call this micrometer with units of “divisions.”

6. Look up the wavelength of a Helium-Neon laser on the internet and, using Equation (1) above, calculate the number of microns that the mirror moved.

7. Divide your answer to step (6) by your answer to step (5). This gives you the number of microns the mirror moves for every division that you turn the knob. Call this number R (for ratio).

8. Your next goal is to determine the sensitivity of your instrument, i.e., the minimum measurable difference in arrival time of the two beams. You measure a difference in arrival time by noticing a change in the fringe pattern. If the fringe pattern changes by one full fringe, then the arrival time changes by one full period, T, of the light wave, and the period relates to the wavelength by T = /c.

 ESTIMATION OF SENSITIVITY: By having one partner adjust the knob and the other watch the fringe pattern, determine the smallest movement in the micrometer knob that can be detected by a shift in the fringe pattern. Switch roles and average your results. Repeat 5 times and average. Multiply the average by R, the microns of movement of the mirror per division on knob. This gives you the minimum path-length difference, *x*min, that you can measure.

9. Now, you just need to convert this to a minimum arrival time difference, *t*min. These are related by comparing them to a full cycle of the waves, i.e.

$$\frac{∆t\_{min}}{T}=\frac{∆x\_{min}}{λ}.$$

 Calculate your minimum measurable arrival time difference.

10. Measure the distance between the beam splitter and one of the mirrors. This is your *L*.

11. While taking care not to disturb the setup, and while watching the fringe pattern, rotate the entire cart on which the apparatus sits by 90o. Do you see any change in the fringe pattern? (You should NOT see a difference.)

Calculation of Minimum Possible Expected Time Difference (in the model with ether).

12. Calculate the speed of the surface of the Earth at the equator due to its rotation.

13. Calculate the speed of the Earth in its orbit about the Sun.

14. The orbital speed of the Sun in its orbit in the Galaxy is determined to be 220 km/s. Considering these three velocity vectors (whose directions you don’t know) calculate the smallest possible speed of the Earth at any moment, i.e. what arrangement of these vectors yields the smallest magnitude of the total vector.

15. Use the smallest possible Earth speed in Equation (2) to calculate the smallest *expected* time difference (if there was an ether frame).

16. Compare your minimum *expected* time difference (answer to #15) with the maximum possible based on your null detection of a shift in the fringe pattern and your minimum *detectable* *t*min (answer to #9). Is your experiment sensitive enough to disprove the ether concept? If not, use Equation (2) and your minimum measurable *t*arrival to calculate the maximum possible speed of the Earth relative to the ether frame.

15. To make your experiment more sensitive, you could use a much larger interferometer. Calculate the minimum *L* for this experiment to succeed.

Lab Report:

One of the lab partners turns in a formal report (due in one week) and the other presents the lab results in a 15-minute oral report to your instructor in his office – schedule a time on the oral lab report Google sheet.

Address the following bullet points in your report:

* Discuss the historical significance of the Michelson interferometer.
* Give a detailed explanation of the derivation of the difference in travel times of the two beams.
* What is the smallest possible *expected* difference in travel time of the beams in your interferometer? Explain the calculation.
* What is the smallest possible *measured* difference in travel time of the beams in your interferometer? Discuss the estimation of your uncertainties and the calculation leading to smallest possible measurement.
* How does your expected travel time difference compare with your uncertainty? Is the Michelson-Morley Experiment feasible with the interferometer you used? How large an interferometer (give minimum of *L*) is needed for this experiment to give a definitive result?