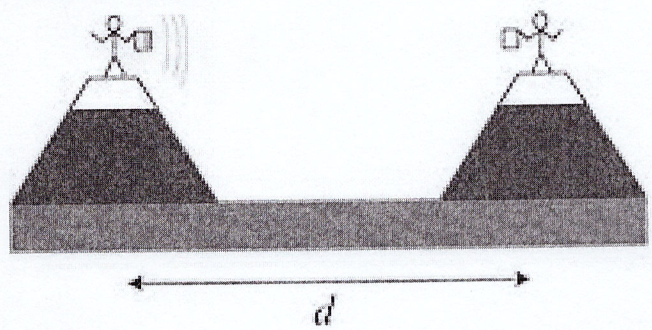
Measuring the Speed of Light

- Recall, that all EMR travel at the speed of light in a vacuum (and we assume the same in air as well)
    - Also recall that the speed of all EMR is uniform if it stays in the same medium
- Measuring the speed of light was not an easy task because light travels so fast and can cover a huge distance almost instantaneously

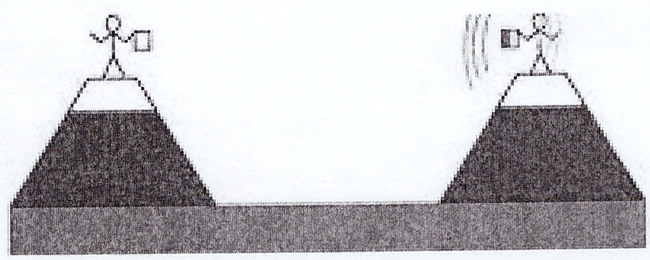
Galileo

- Galileo stood on one hilltop while his assistant stood on another, both holding covered lanterns
- Galileo opened his lantern first
- As soon as his assistant saw the light from Galileo, the assistant opened his to shine a light back
- Galileo hoped that by knowing the distance between the two hilltops and the time it took for the light to travel between them, he would be able to calculate the speed of light.
- In the end, Galileo realized that the small time difference he measured was probably due to human reaction time and his poor methods/instruments to actually measure time

Lantern is opened

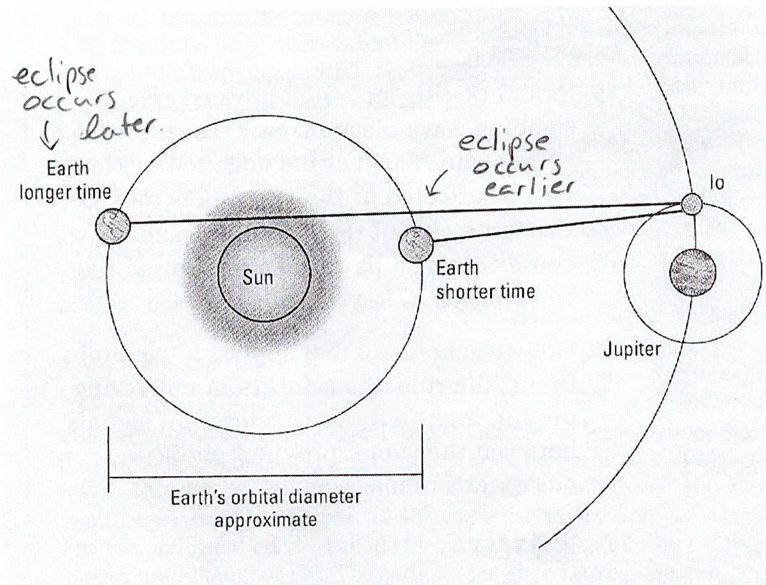


Second lantern is opened when light from first arrives



Ole Romer

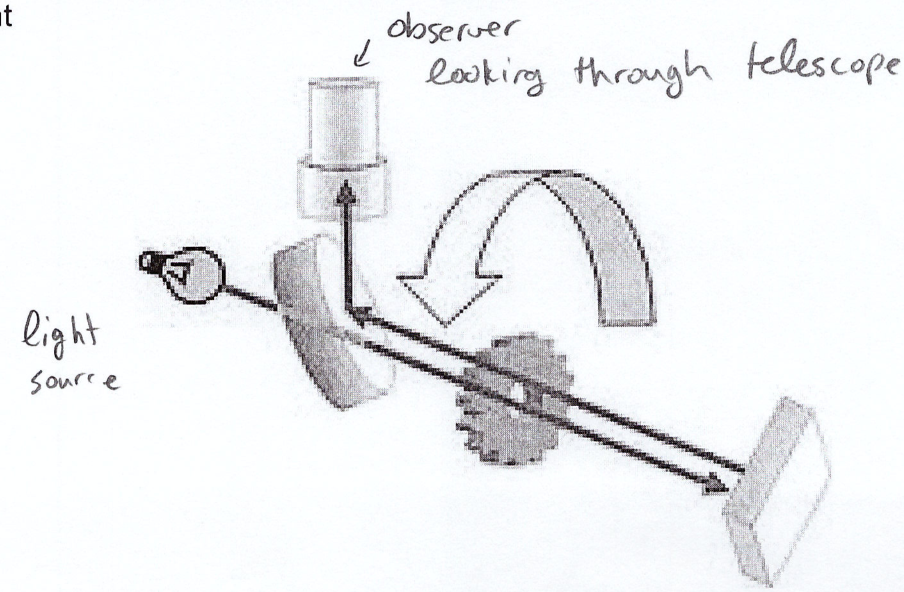
- Measure the speed of light based on the eclipse of one of Jupiter's moons
- At certain times of the year, Earth and Jupiter are different distances from each other depending where they are in their orbits
- Romer had noticed that at different times through out the year, there was a delay in the time he could see Jupiter eclipse one of its moons
- Romer explained this observation due to the different distances the light had to travel from Jupiter to Earth
- Because Romer had some rough figures on the distance of the planets in their orbits, he was able to make a rough calculation of the speed of light
- By today's standards he was quite far off, but it was the first attempt to measure the speed of light that actually came up with an answer



▲ **Figure 13.21** Earth's orbital diameter causes the eclipse of Io to occur at different times because of the extra distance the light must travel when Earth is farthest from Jupiter.

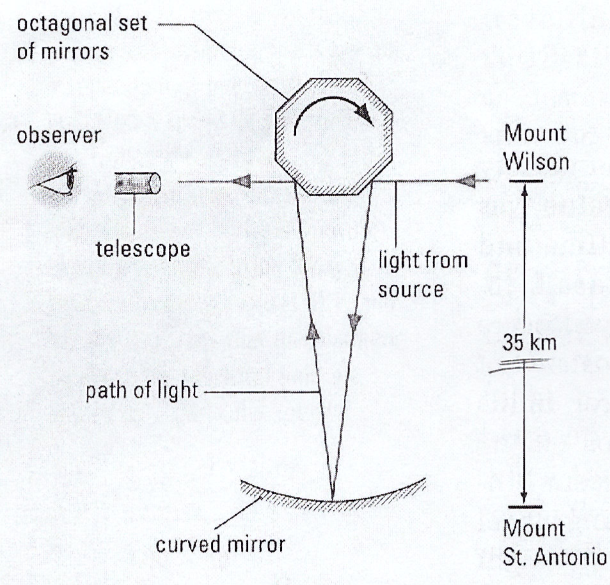
FIZEAU

- He shone a narrow, strong beam of light between the teeth/cog of a spinning gear
- The light continued on, travelling a long distance (about 8.5km) and hit a mirror and bounded back the way it came
- If the gear was spinning with the right period, one tooth of the gear would have exactly the right amount of time to move in the way of the returning light, block it from view and the observer would not be able to see the light. Or if the gear was spinning with the right period, one tooth of the gear would have exactly the right amount of time to rotate by, leaving an opening for the light to pass by. Therefore the observer would only see a continuous stream of light.
- He was actually very accurate, with only about a 5% error of the actual speed of light



MICHELSON

- He used a spinning mirror apparatus, instead of spinning gear
- The reason his method was so accurate is that he used a rotating eight sided mirror (or any multisided mirror would work).
- A beam of light hit one of the sides and reflected to a stationary mirror
- This beam bounced back to the rotating mirror. As long as the rotating mirror has spun exactly 1/8th of a turn, the next side is in the correct position to reflect the light exactly back to an observer looking through a telescope



▲ **Figure 13.24** Michelson's experimental apparatus to measure the speed of light

EXAMPLES:

1. When Michelson did his experiment with the curved mirror 35.0km away. He found that the 8-sided mirror needed to spin at 32000 rpm. Using this information, determine the speed of light. ↳ f

$d = 35.0\,km \times \left(\frac{10^3\,m}{1\,km}\right) = 35000\,m$

$f = \frac{32000\,rev.}{1\,min} \times \left(\frac{1\,min}{60\,s}\right) = 533.\bar{3}\,rev/s = 533.\bar{3}\,Hz$

$v = \frac{d}{t}$ ③

↳ $t = \frac{1}{8}T$ ②

↳ $T = \frac{1}{f}$ ①

① $T = \frac{1}{f} = \frac{1}{533.\bar{3}\,Hz}$

$T = 0.001875\,s$

② $t = \frac{1}{8}T = \frac{1}{8}(0.001875\,s)$

$t = 2.3437... \times 10^{-4}\,s$

③ $v = \frac{d}{t} = \frac{(35000\,m \times 2)}{2.3437... \times 10^{-4}\,s}$

$v = 2.9866... \times 10^{8}\,m/s$

$\boxed{v = 2.99 \times 10^{8}\,m/s}$

2. Using an experimental set-up similar to Michelson, using a 6-sided mirror, students found the speed of light to be 2.95×10^8 m/s. The mirrors were placed 45.0km from the fixed mirror. What was the frequency of rotation of the mirror?

$v = 2.95 \times 10^8 \text{ m/s}$

$d = 45.0 \text{ km} \times \left(\frac{10^3 \text{ m}}{1 \text{ km}} \right) = 45000 \text{ m}$

$f = ?$

$f = \frac{1}{T}$ (3)

$T = 6t$ (2)

$v = \frac{d}{t}$ (1)

(1) $v = \frac{d}{t} \Rightarrow t = \frac{d}{v} = \frac{(45000 \text{ m} \times 2)}{2.95 \times 10^8 \text{ m/s}} = 3.0508... \times 10^{-4} \text{ s}$

(2) $T = 6t = 6(3.0508... \times 10^{-4} \text{ s}) = 0.0018305... \text{ s}$

(3) $f = \frac{1}{T} = \frac{1}{0.0018305... \text{ s}} = 546.296... \text{ Hz}$

$f = 546 \text{ Hz}$

***Now try pg. 198 # 10, 12-14, 17, 20, 22 & Practice Problems ***

Practice Problems

1. An 8-sided set of rotating mirrors rotates at 545Hz in an experiment similar to that of Michelson. How far away should the fixed mirror be placed in order to correctly measure the speed of light? **[3.44×10^4 m]**

2. When the Earth and Jupiter are on the same side of the sun they are separated by 6.28×10^{11}m and when they are on opposite sides they are separated by 9.28×10^{11}m. Jupiter's eclipse of Io is 16 minutes later when they Earth is farther away than when it is at the closest approach. Determine the speed of light. **[3.1×10^8 m/s]**

3. Using a similar approach to Michelson, a student sets up a 64-sided set of rotating mirrors, 8.00km away from the fixed mirror. What minimum frequency of rotation would be required to successfully measure the speed of light? **[293 Hz]**

4. A 12-sided set of rotating mirrors is turning at 1813Hz. If a fixed mirror is located 6.55km away from the rotating mirror and the light is reflected correctly, what value for the speed of light would be obtained? **[2.85×10^8 m/s]**

5. Why was Galileo's original experiment to determine the speed of light unsuccessful?

6. Explain why, in a Michelson-type experiment, the rotating mirrors have to turn at a very precise frequency in order for light to reach a stationary observer.

7. Explain why the periodic motion of Jupiter's moon Io appears to be constantly changing when observed from Earth?

Answers

5. The speed of light is incredibly fast and back in Galileo's time, he didn't have very precise instruments for measuring time. Another reason Galileo's experiment was unsuccessful was due to fact of measuring a time difference depended on seeing the light and uncovering their lantern was more due to human reaction time and not the actual time require for light to travel a certain distance.

6. If the rotating mirror did not turn exactly 1/8th (if we are using an 8-sided mirror), the reflected light coming back from the fixed mirror would hit the rotating mirror at a different angle and be reflect elsewhere and not end up being reflected into a telescope for the observer to see.

7. Since the Earth orbits the Sun faster and Jupiter, Jupiter and Earth are continuously at different distances from each other. Therefore, different distances between the plants require different amounts of time for light to travel those different distances (remember the speed of light is uniform in the same medium). This will cause the eclipse of Jupiter's of the moon, Io, to occur at different times depending on the position of the planets; making the periodic motion of Io appear to be constantly changing.