# Measuring the Speed of Light

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# Why is the speed of light important astronomically?

- Key to understanding how what we observe relates to what is actually happening and when
- Led Einstein to his theories of Special and General Relativity which are fundamental to understanding the cosmos

Speed in vacuo:

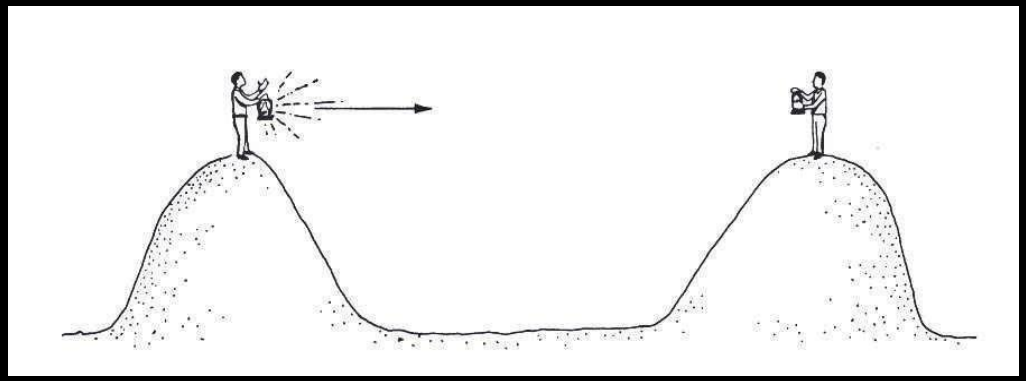
c = 299,792,458 metres per second

# Outline

- Pioneers – and their methods
  - Galileo, Rømer, Bradley, Fizeau, Foucault, Michelson
- Measuring c in your garage
  - The maths
  - Apparatus
- Demonstrations
- Possible projects

# First attempts

- Early philosophers' opinions were divided over whether the speed of light was finite or infinite
- Galileo was among the first to propose an experiment to measure it

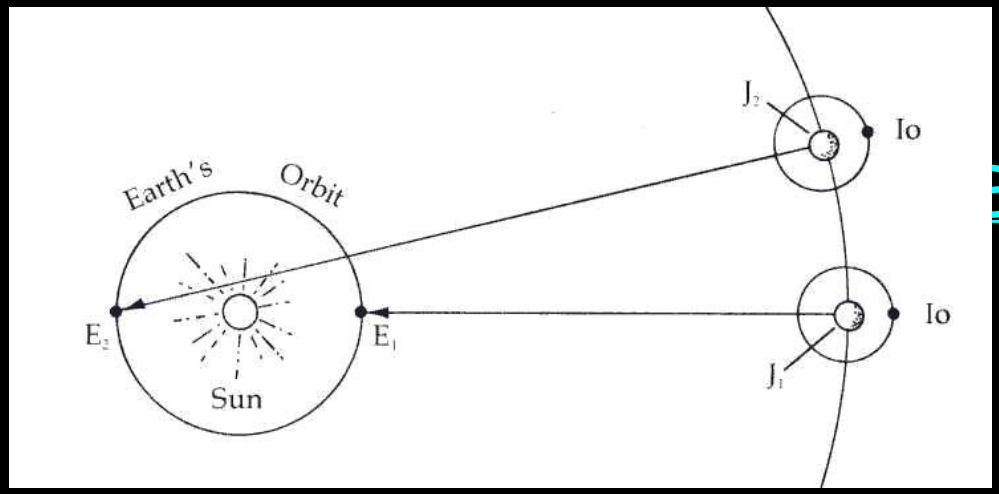


Experiment proposed in 1638 but he claimed to have carried it out earlier

Experiment repeated by Accademia del Cimento of Florence in 1667

# Ole Rømer (~1670)

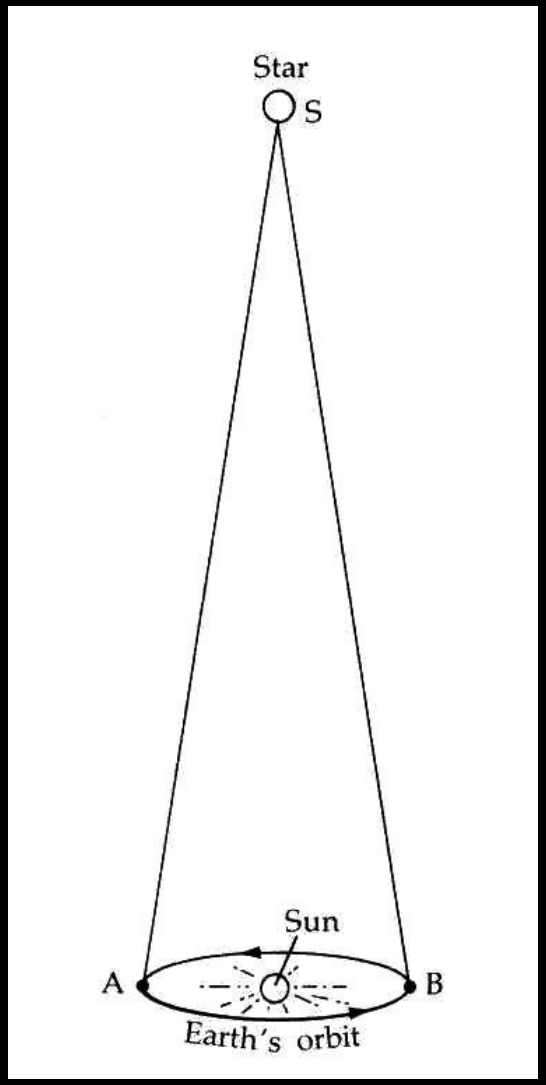
- Used the orbiting of Jupiter's moon Io (moving into or out of Jupiter's shadow) as a ticking clock
- Having determined the orbital period of Io (the 'clock tick') he argued the ticks would be seen later when Jupiter was further from the Earth




Speed of light = Earth orbit diameter / Maximum tick delay

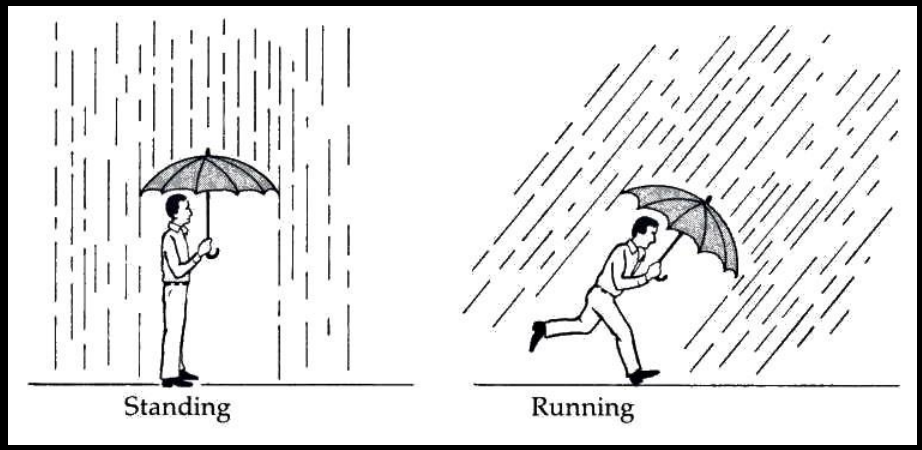
# The Aberration of Light

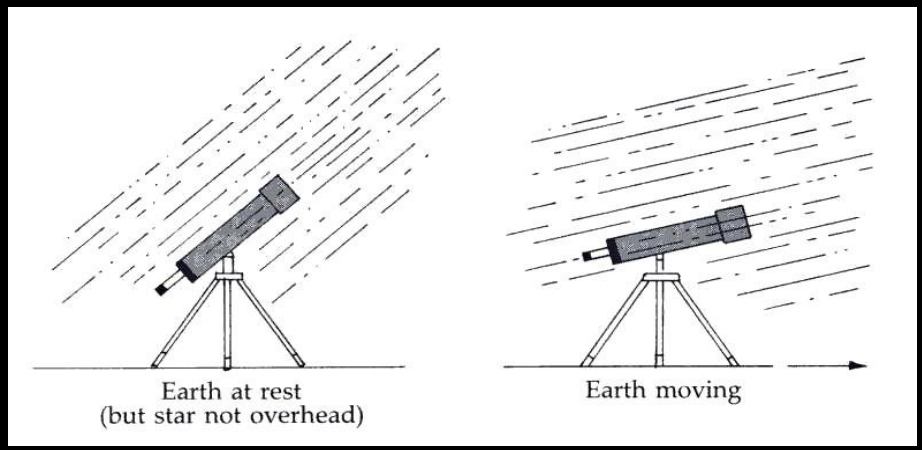
- Discovered as a result of the search for stellar parallax
- Small circular/elliptical motions of stars observed over a year
- Aberration correctly explained by James Bradley in 1728 as due to the finite speed of light



# Understanding Aberration

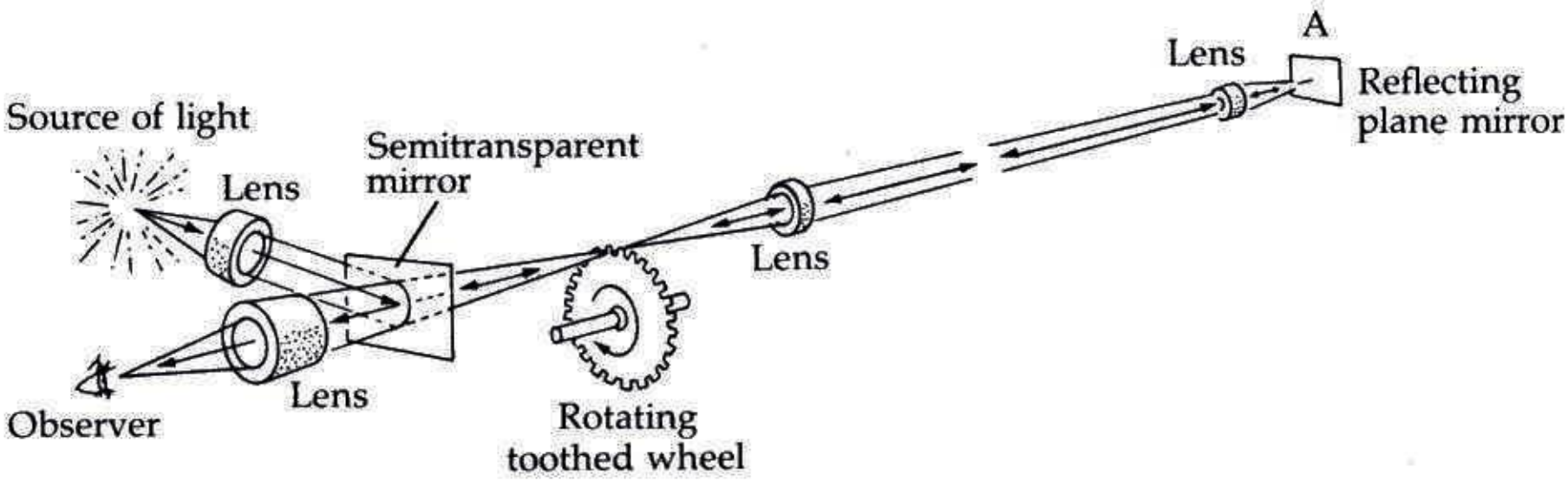
- Aberration is caused by the motion of the observer, not the position of the observer
- Aberration angle depends on ratio of the Earth's orbital speed to light speed



# Fizeau's toothed wheel

- 1847 – Armand Fizeau measured the speed of light terrestrially
- Spinning toothed wheel passes pulses of light to a distant mirror
- Reflected pulses are blocked upon return if the wheel is spun fast enough



# Foucault's rotating mirror

- Originally suggested by Wheatstone in 1834
- Foucault made his measurement in 1860
- Improved by Newcomb (1882) who introduced a multi-faceted mirror
- Further refined by Michelson (1879, 1882, 1929)
- Measurement in vacuo – Pearson and Pease (1931)

# Michelson's notebook



Experimental Determination of the Velocity of Light.

Albert A. Michelson
Master, U.S. Navy.

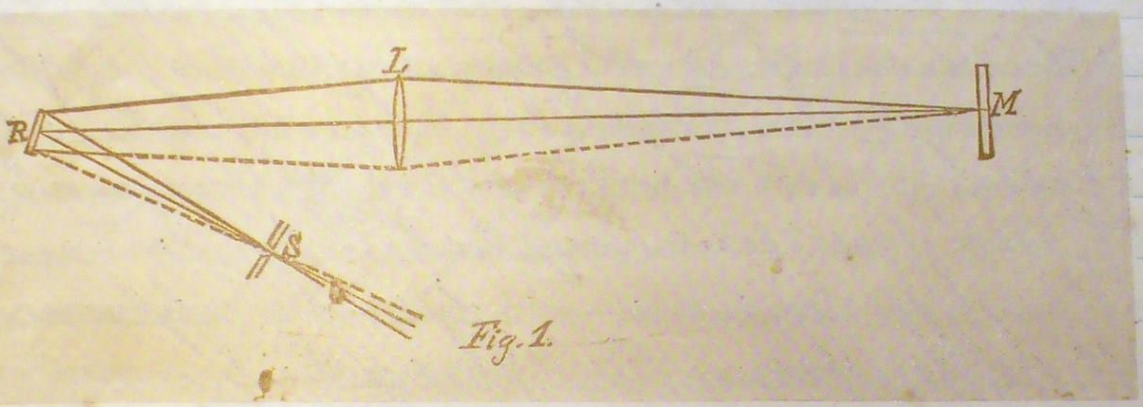



Fig. 1.

Let S, Fig. 1, be a slit through which light passes falling on R, a mirror free to rotate about an axis at right angles to the plane of the paper; L, a lens of great focal length upon

# Electronic methods

- 1925 Karolus & Mittelstaedt used a Kerr cell as an optical modulator (shutter) operating at several MHz
- 1937 Anderson refined the Kerr cell method
- 1947 Essen & Gordon-Smith used a microwave cavity resonator
- 1949 Aslakson used radar

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# Let me count the ways...

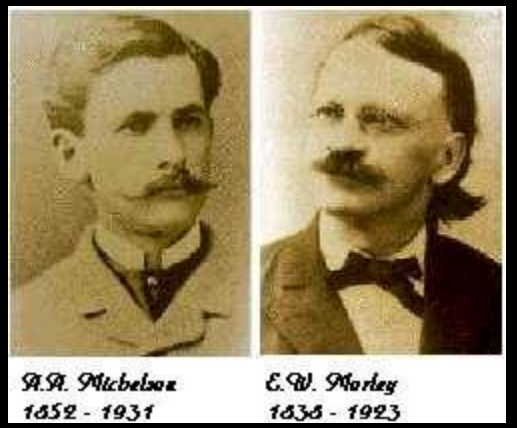
| | |
|---|---|
| 1638 Galileo | Shuttered Lanterns |
| 1670 Rømer | Jupiter's moons |
| 1728 Badley | Aberration of Light |
| 1847 Fizeau | Toothed Wheel |
| 1860 Foucault | Rotating Mirror |
| 1882 Newcomb, Michelson | Multi-faceted Rotating Mirror |
| 1925 Karolus et al | Kerr Cell |
| 1949 Bergstrand | Geodimeter |
| 1950 Essen | Microwave Cavity |
| 1951 Froome | Microwave Interferometer |
| 1955 Floorman | Radio Frequency |
| 1955 Rank et al | Band Spectra |
| 1956 Wadley | Tellurometer |
| 1966 Karolus et al | Ultrasonic Modulator |
| 1972 Evenson et al | Laser |

# Increasing Accuracy

| Date | Experimenter | Method | Speed (m/s) | Uncertainty (± m/s) |
|---|---|---|---|---|
| 1876 | Cornu | Toothed wheel | 299,990,000 | 200,000 |
| 1880 | Michelson | Rotating mirror | 299,910,000 | 50,000 |
| 1883 | Newcomb | Rotating mirror | 299,860,000 | 30,000 |
| 1883 | Michelson | Rotating mirror | 299,853,000 | 60,000 |
| 1926 | Michelson | Rotating mirror | 299,796,000 | 4000 |
| 1928 | Karolus and Mittelstaedt | Kerr Cell | 299,778,000 | 10,000 |
| 1932 | Michelson and others | Rotating mirror | 299,774,000 | 11,000 |
| 1941 | Anderson | Kerr Cell | 299,776,000 | 14,000 |
| 1950 | Bergstrand | Geodimeter | 299,792,700 | 250 |
| 1950 | Essen | Microwave cavity | 299,792,500 | 3000 |
| 1951 | Aslakson | Shoran radar | 299,794,200 | 1900 |
| 1952 | Froome | Microwave interferometer | 299,792,600 | 700 |
| 1954 | Florman | Microwave interferometer | 299,795,100 | 1900 |
| 1957 | Bergstrand | Geodimeter | 299,792,850 | 160 |
| 1958 | Froome | Microwave interferometer | 299,792,500 | 100 |
| 1965 | Kolibayev | Geodimeter | 299,792,600 | 60 |
| 1967 | Grosse | Geodimeter | 299,792,500 | 50 |
| 1972 | Evenson and others | Laser | 299,792,457.4 | 1.1 |
| 1974 | Blaney and others | Laser | 299,792,459.0 | 0.6 |
| 1976 | Woods and others | Laser | 299,792,458.8 | 0.2 |
| 1977 | Monchalin and others | Laser | 299,792,457.6 | .73 |

# Is there an aether?

- Michelson-Morley experiment showed that there is no 'aether' through which light travels

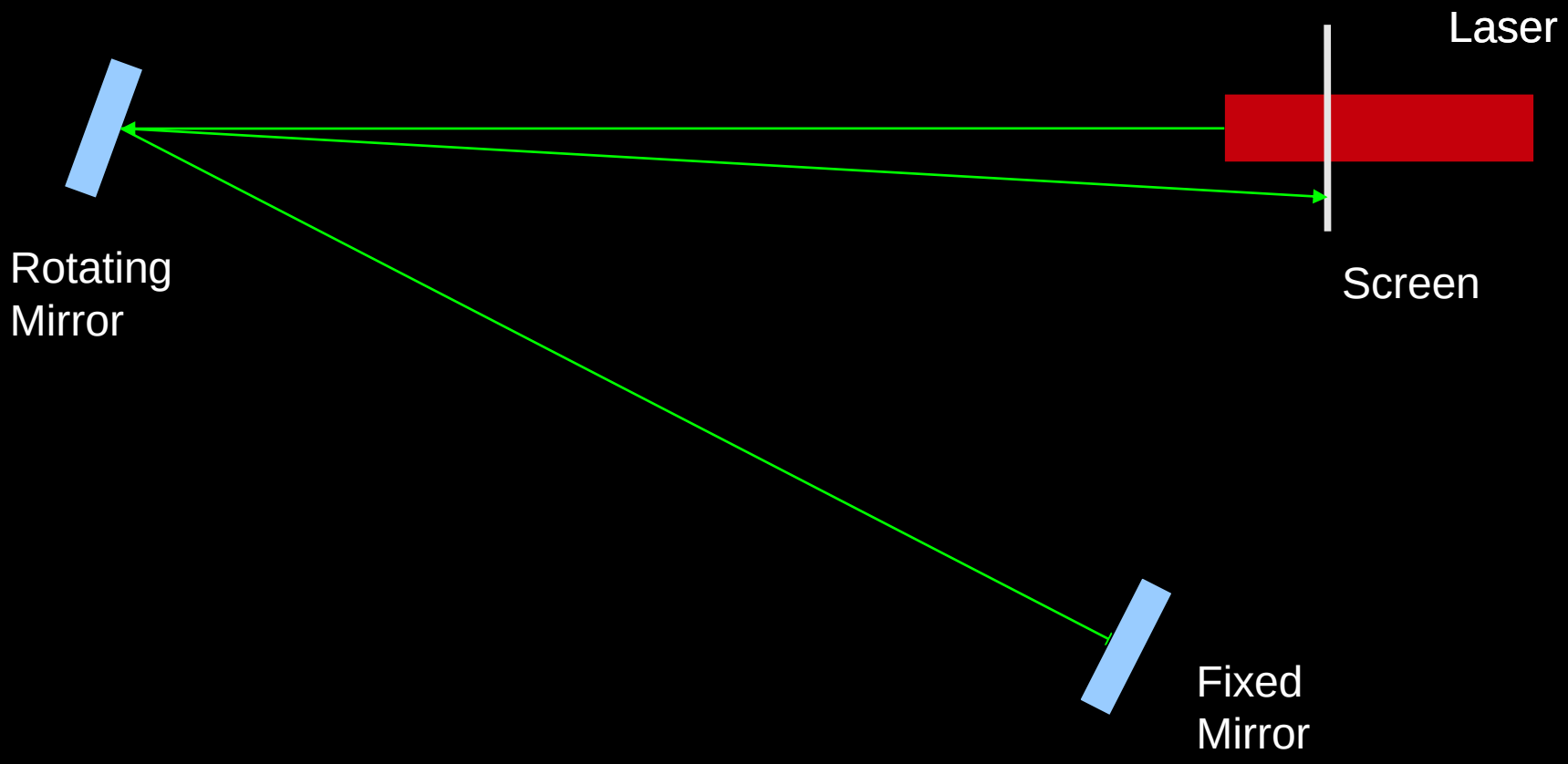



- Special and General Relativity are founded on the assumption that c is constant – and independent of the speed of the source or the observer

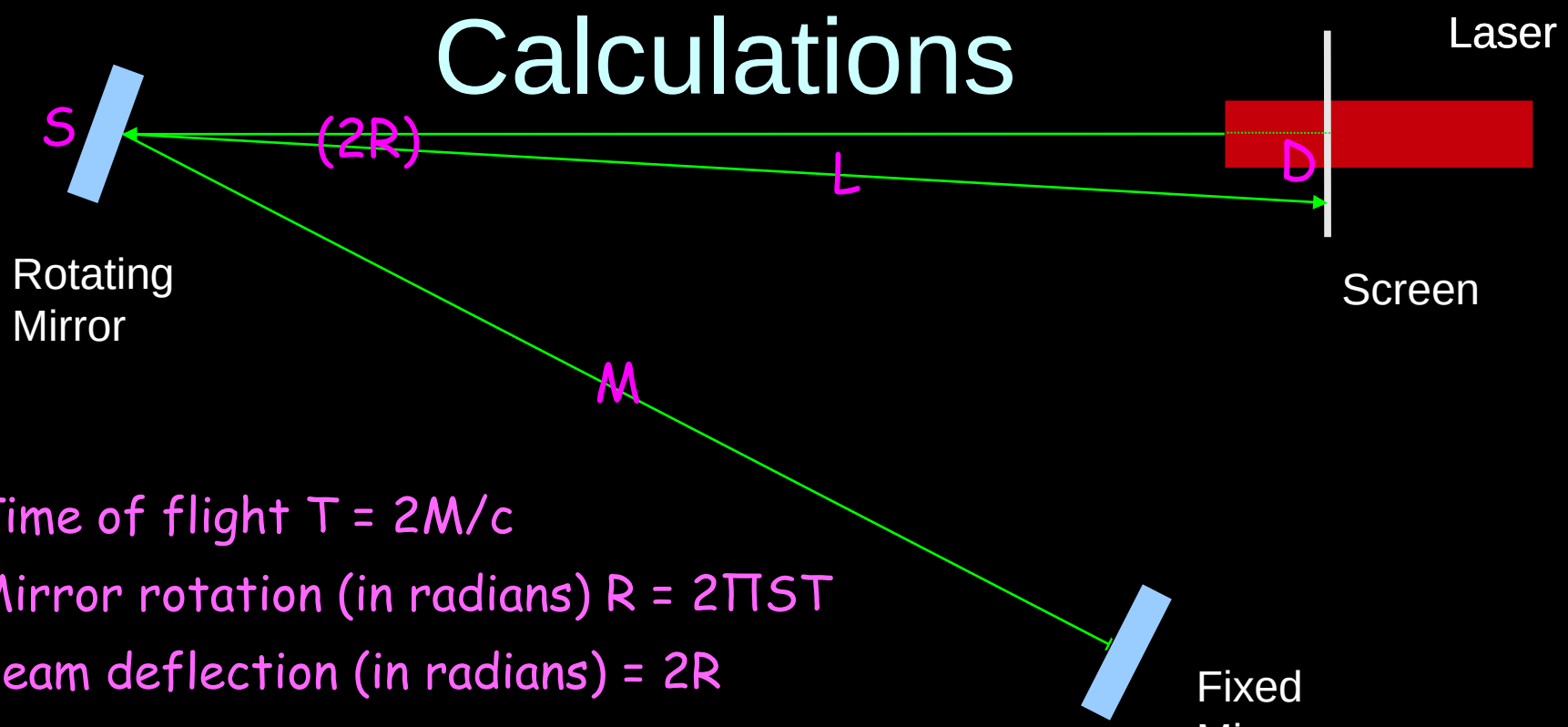
# Do It Yourself

- Rotating Mirror
- Pulsed Laser
- Microwave

# Rotating Mirror Method



# Calculations




Time of flight T = 2M/c

Mirror rotation (in radians) R = 2ΠST

Beam deflection (in radians) = 2R

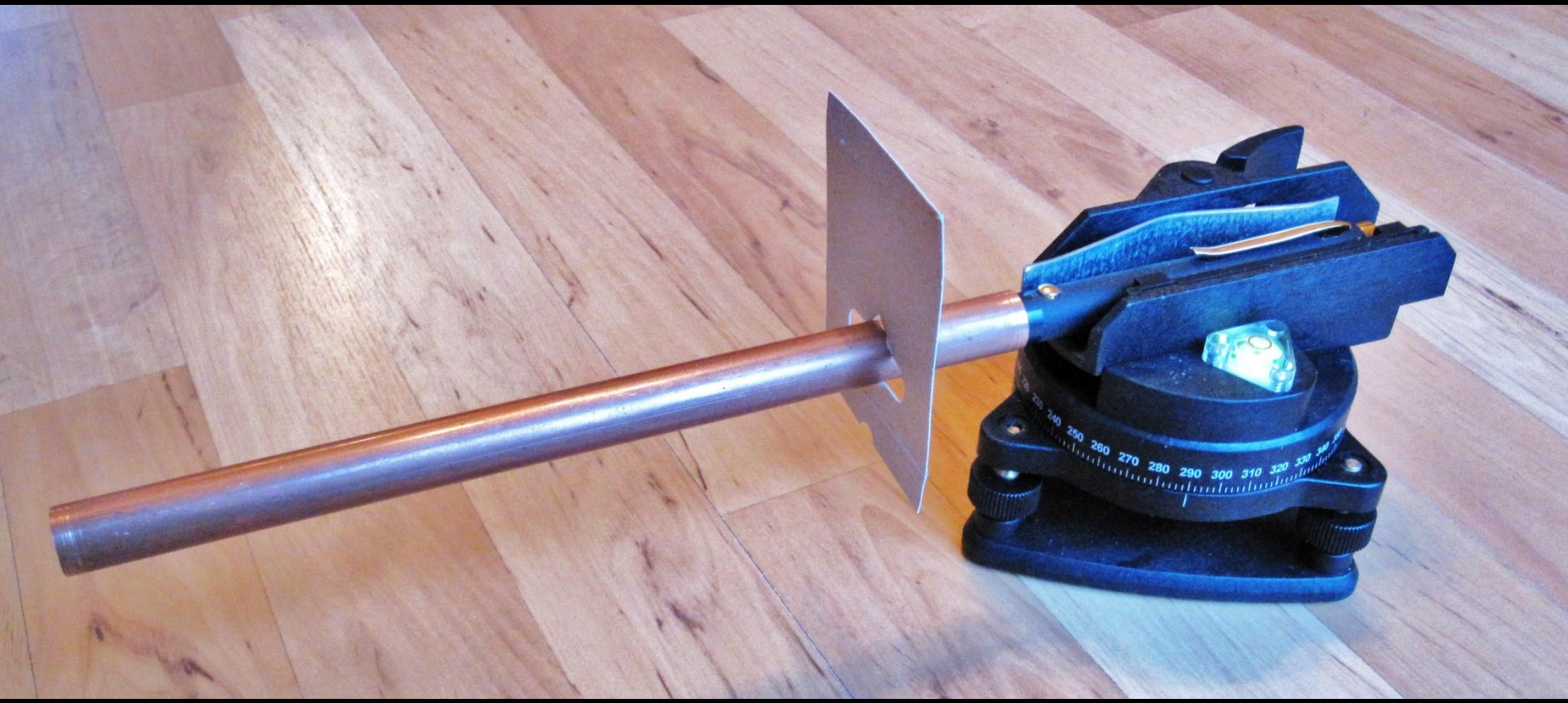
Beam deflection on screen D = 2RL

Putting it all together: c = 8ΠMLS/D m/s

For current experiment, expect D to be approx:

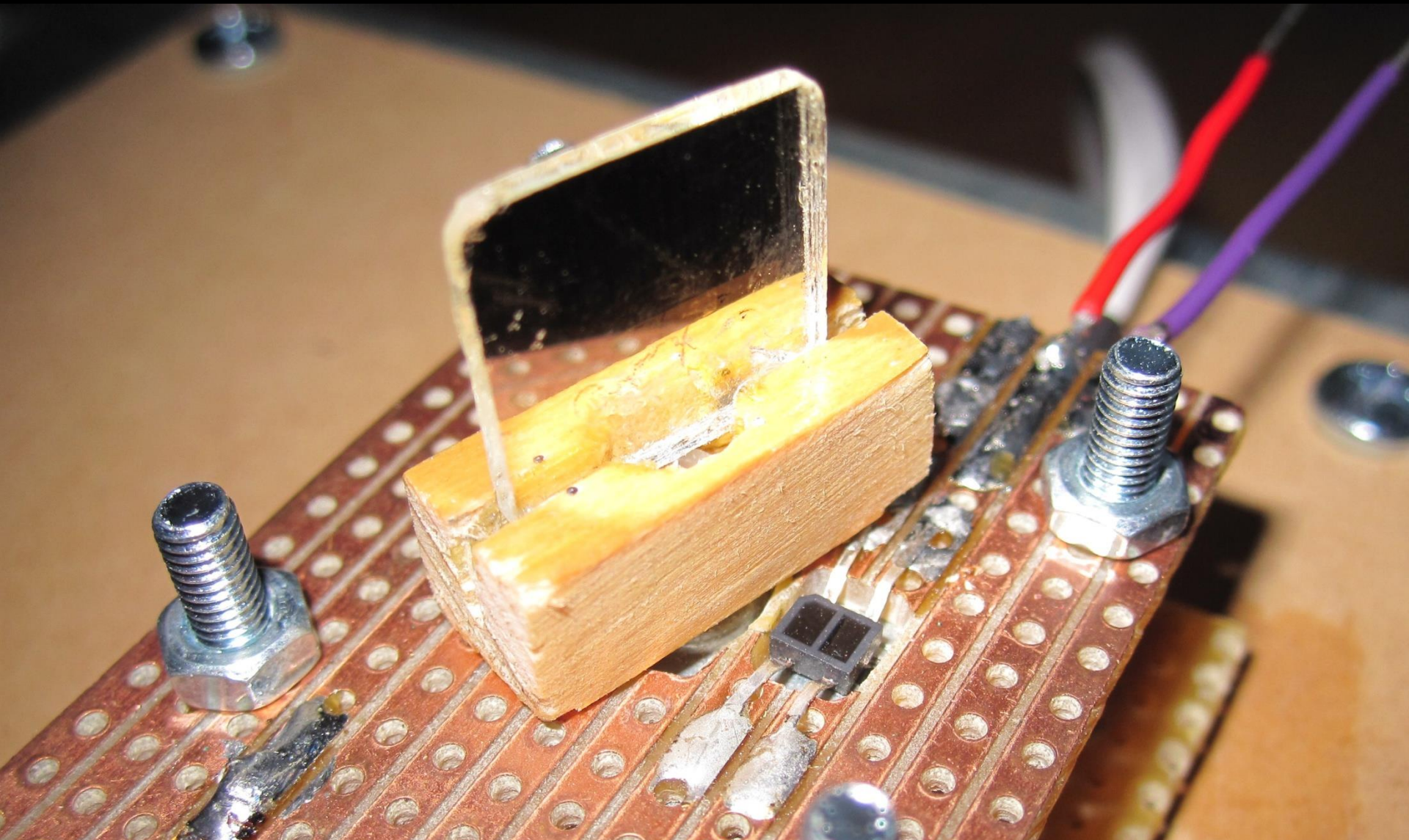
$D = \frac{8\Pi x14x14x130}{299792458} \sim 2.1mm$

# Laser and screen



# Rotating Mirror

# Rotating mirror (~130 rev/s)



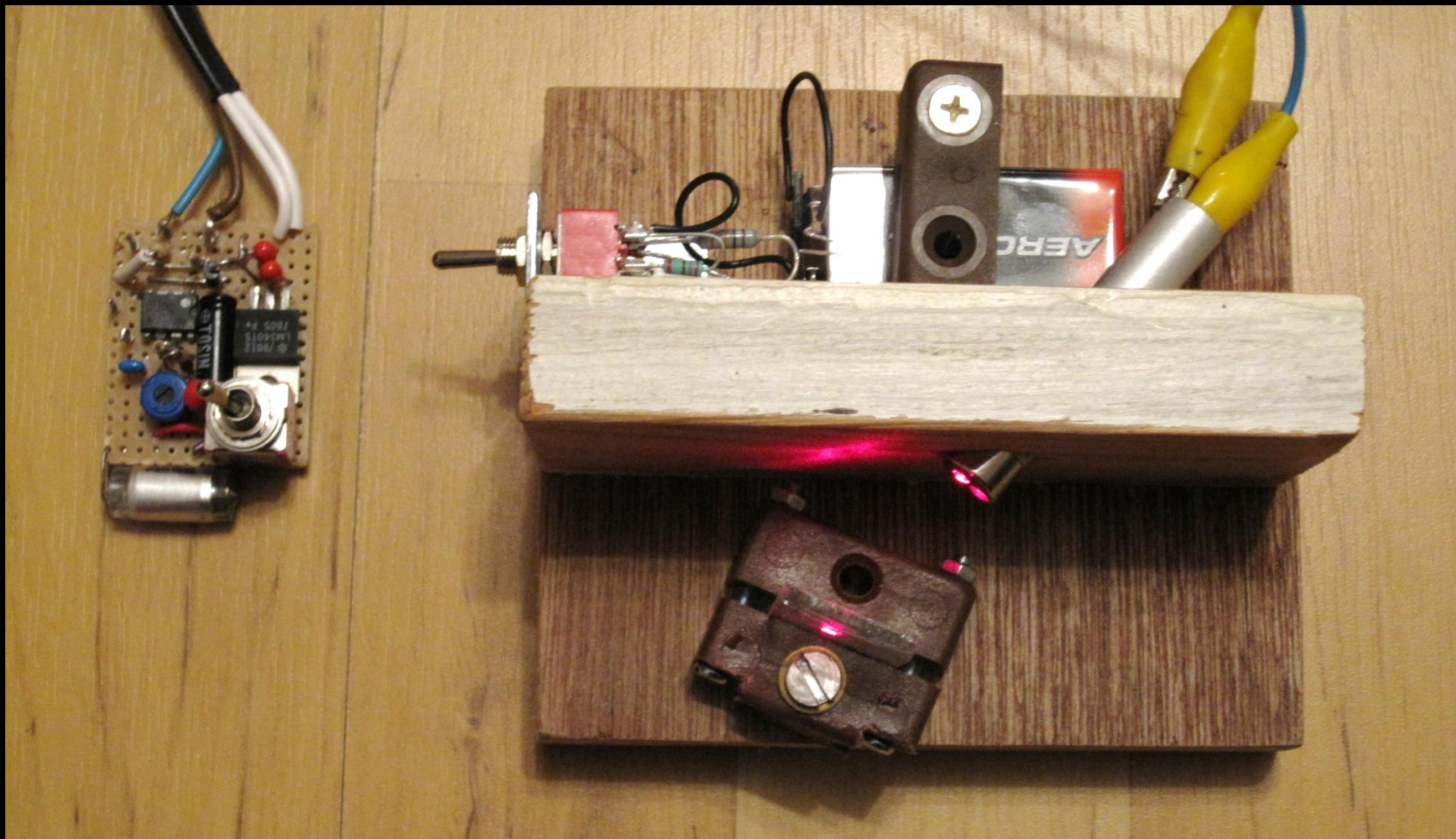
# Rotating mirror (~300 rev/s)

# Fixed Mirror

# Pulsed Laser

- Laser diode switched on/off at ~100kHz
- Rising edges of light pulses detected by photodiodes and displayed on oscilloscope
- Delay (T) in rising edge observed when long path (P) in place using mirrors
- $c = P / T$
- 30 metre round trip $\rightarrow$ delay of 100nS

# Pulsed Laser, Beam Splitter, Reference Photodiode

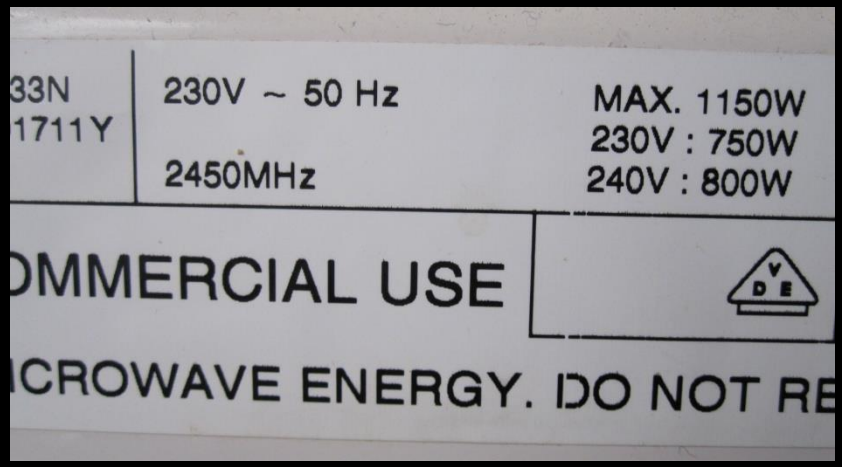


# Receiving Photodiode

# Multiple reflection pulsed laser

# Microwave

- Standing wave in microwave oven produces 2 hot spots per wavelength $\lambda$
- Frequency f of microwave oven is 2450MHz




$c = f \times \lambda$


Cheese slices used as hot spot detectors

# Demonstrations

# Observing project

- Record timings of eclipses of Io over a period of up to a year, to enable a rough confirmation of Rømer's result
- The full calculations could be quite complex if allowing for:
  - Ellipticity of Earth's orbit
  - Ellipticity of Jupiter's orbit
  - Tilt of Io's orbit
  - Orbital resonances of Jupiter's moons

# Construction projects

- Improve rotating mirror method
  - Surface silvered rotating mirror
  - Corner cube reflector
  - Higher rotation speed
  - Improved optical design
- Improve multiple reflection laser method
  - Reduce beam divergence
  - Faster pulse rise time

# Workshops

- Special Relativity
- General Relativity

# References


A http://en.wikipedia.org/wiki/Speed_of_light
B Relativity and its roots. Banesh Hoffmann. 1983. Scientific American Books. Distributed by W H Freedman & Co
C Geometrical and Physical Optics. R S Longhurst. 3rd Edition 1973. Longman.
D http://en.wikipedia.org/wiki/R%C3%B8mer%27s_determination_of_the_speed_of_light
E Challenges of Astronomy. W Schlosser et al. pp83-87
F http://en.wikipedia.org/wiki/Aberration_of_light
G http://galileoandeinstein.physics.virginia.edu/lectures/spedlite.html
H The Project Gutenberg EBook of Experimental Determination of the Velocity of Light, by Albert A. Michelson
I http://www.magicdave.com/ron/Does%20the%20Speed%20of%20Light%20Slow%20Down%20Over%20Time.html
J The Theory of Relativity. Albert Einstein. 4th Edition 1921. Methuen.


Also - some web urls as given in the notes.

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# Postscript - is c constant??

- Light does slow down when passing through matter (Refractive Index)
- If c changed over time, other physical constants must also change
  - e.g. permittivity and permeability of free space - hence charge on an electron, Planck's constant, fine structure constant...
  - hence ratios of spectral lines of distant quasars would have changed – they haven't