= Fizeau ? Foucault apparatus =

Fizeau ? Foucault apparatus is a term sometimes used to refer to two types of instrument historically used to measure the speed of light . The conflation of the two instrument types arises in part because Hippolyte Fizeau and Léon Foucault had originally been friends and collaborators . They worked together on such projects as using the Daguerreotype process to take images of the Sun between 1843 and 1845 and characterizing absorption bands in the infrared spectrum of sunlight in 1847 .

In 1834 , Charles Wheatstone developed a method of using a rapidly rotating mirror to study transient phenomena , and applied this method to measure the velocity of electricity in a wire and the duration of an electric spark . He communicated to François Arago the idea that his method could be adapted to a study of the speed of light . Arago expanded upon Wheatstone 's concept in an 1838 publication , emphasizing the possibility that a test of the relative speed of light in air versus water could be used to distinguish between the particle and wave theories of light .

In 1845 , Arago suggested to Fizeau and Foucault that they attempt to measure the speed of light . Sometime in 1849 , however , it appears that the two had a falling out , and they parted ways pursuing separate means of performing this experiment . In 1848 ? 49 , Fizeau used , not a rotating mirror , but a toothed wheel apparatus to perform an absolute measurement of the speed of light in air . In 1850 , Fizeau and Foucault both used rotating mirror devices to perform relative measures of the speed of light in air versus water . Foucault used a scaled @-@ up version of the rotating mirror apparatus to perform an absolute measurement of the speed of light in 1862 . Subsequent experiments performed by Marie Alfred Cornu in 1872 ? 76 and by Albert A. Michelson in 1877 ? 1931 used improved versions of the toothed wheel and rotating mirror experiments to make steadily more accurate estimates of the speed of light .

= = Fizeau 's determination of the speed of light = =

In 1848 ? 49 , Hippolyte Fizeau determined the speed of light between an intense light source and a mirror about 8 km distant . The light source was interrupted by a rotating cogwheel with 720 notches that could be rotated at a variable speed of up to hundreds of times a second . (Figure 1) Fizeau adjusted the rotation speed of the cogwheel until light passing through one notch of the cogwheel would be completely eclipsed by the adjacent tooth . Spinning the cogwheel at 3 , 5 and 7 times this basic rotation rate also resulted in eclipsing of the reflected light by the cogwheel teeth next in line . Given the rotational speed of the wheel and the distance between the wheel and the mirror , Fizeau was able to calculate a value of 313000 km / s for the speed of light . It was difficult for Fizeau to visually estimate the intensity minimum of the light being blocked by the adjacent teeth , and his value for light 's speed was about 5 % too high .

The early @-@ to @-@ mid 1800s were a period of intense debate on the particle @-@ versus @-@ wave nature of light . Although the observation of the Arago spot in 1819 may seem to have settled the matter definitively in favor of Fresnel 's wave theory of light , various concerns continued to appear to be addressed more satisfactorily by Newton 's corpuscular theory . Arago had suggested in 1838 that a differential comparison of the speed of light in air versus water would serve to prove or disprove the wave nature of light . In 1850 , racing against Foucault to establish this point , Fizeau engaged L.F.C. Breguet to build a rotary @-@ mirror apparatus in which he split a beam of light into two beams , passing one through water while the other traveled through air . Beaten by Foucault by a mere seven weeks , he confirmed that the speed of light was greater as it traveled through air , validating the wave theory of light .

= = Foucault 's determination of the speed of light = =

In 1850 and in 1862 , Léon Foucault made improved determinations of the speed of light substituting a rotating mirror for Fizeau 's toothed wheel . (Figure 2) The apparatus involves light from slit S reflecting off a rotating mirror R , forming an image of the slit on the distant stationary

mirror M , which is then reflected back to reform an image of the original slit . If mirror R is stationary , then the slit image will reform at S regardless of the mirror 's tilt . The situation is different , however , if R is in rapid rotation .

As the rotating mirror R will have moved slightly in the time it takes for the light to bounce from R to M and back , the light will be deflected away from the original source by a small angle .

As seen in Figure 3 , the displaced image of the source (slit) is at an angle 2? from the source direction .

Guided by similar motivations as his former partner , Foucault in 1850 was more interested in settling the particle @-@ versus @-@ wave debate than in determining an accurate absolute value for the speed of light . Foucault measured the differential speed of light versus water by inserting a tube filled with water between the rotating mirror and the distant mirror . His experimental results , announced shortly before Fizeau announced his results on the same topic , were viewed as " driving the last nail in the coffin " of Newton 's corpuscle theory of light when it showed that light travels more slowly through water than through air . Newton had explained refraction as a pull of the medium upon the light , implying an increased speed of light in the medium . The corpuscular theory of light went into abeyance , completely overshadowed by wave theory . This state of affairs lasted until 1905 , when Einstein presented heuristic arguments that under various circumstances , such as when considering the photoelectric effect , light exhibits behaviors indicative of a particle nature .

In contrast to his 1850 measurement , Foucault 's 1862 measurement was aimed at obtaining an accurate absolute value for the speed of light , since his concern was to deduce an improved value for the astronomical unit . At the time , Foucault was working at the Paris Observatory under Urbain le Verrier . It was le Verrier 's belief , based on extensive celestial mechanics calculations , that the consensus value for the speed of light was perhaps 4 % too high . Technical limitations prevented Foucault from separating mirrors R and M by more than about 20 meters . Despite this limited path length , Foucault was able to measure the displacement of the slit image (less than 1 mm) with considerable accuracy . In addition , unlike the case with Fizeau 's experiment (which required gauging the rotation rate of an adjustable @-@ speed toothed wheel) , he could spin the mirror at a constant , chronometrically determined speed . Foucault 's measurement confirmed le Verrier 's estimate . His 1862 figure for the speed of light (298000 km / s) was within 0 @.@ 6 % of the modern value .

= = Cornu 's refinement of the Fizeau experiment = =

At the behest of the Paris Observatory under le Verrier , Marie Alfred Cornu repeated Fizeau 's 1848 toothed wheel measurement in a series of experiments in 1872 ? 76 . The goal was to obtain a value for the speed of light accurate to one part in a thousand . Cornu 's equipment allowed him to monitor high orders of extinction , up to the 21st order . Instead of estimating the intensity minimum of the light being blocked by the adjacent teeth , a relatively inaccurate procedure , Cornu made pairs of observations on either side of the intensity minima , averaging the values obtained with the wheel spun clockwise and counterclockwise . An electric circuit recorded the wheel rotations on a chronograph chart which enabled precise rate comparisons against the observatory clock , and a telegraph key arrangement allowed Cornu to mark on this same chart the precise moments when he judged that an extinction had been entered or exited . His final experiment was run over a path nearly three times as long as that used by Fizeau , and yielded a figure of 300400 km / s that is within 0 @.@ 2 % of the modern value .

= = Michelson 's refinement of the Foucault experiment = =

It was seen in Figure 2 that Foucault placed the rotating mirror R as close as possible to lens L so as to maximize the distance between R and the slit S. As R rotates , an enlarged image of slit S sweeps across the face of the distant mirror M. The greater the distance RM , the more quickly that the image sweeps across mirror M and the less light is reflected back . Foucault could not increase the RM distance in his folded optical arrangement beyond about 20 meters without the image of the

slit becoming too dim to accurately measure .

Between 1877 and 1931 , Albert A. Michelson made multiple measurements of the speed of light . His 1877 ? 79 measurements were performed under the auspices of Simon Newcomb , who was also working on measuring the speed of light . Michelson 's setup incorporated several refinements on Foucault 's original arrangement . As seen in Figure 5 , Michelson placed the rotating mirror R near the principal focus of lens L (i.e. the focal point given incident parallel rays of light) . If the rotating mirror R were exactly at the principal focus , the moving image of the slit would remain upon the distant plane mirror M (equal in diameter to lens L) as long as the axis of the pencil of light remained on the lens , this being true regardless of the RM distance . Michelson was thus able to increase the RM distance to nearly 2000 feet . To achieve a reasonable value for the RS distance , Michelson used an extremely long focal length lens (150 feet) and compromised on the design by placing R about 15 feet closer to L than the principal focus . This allowed an RS distance of between 28 @.@ 5 to 33 @.@ 3 feet . He used carefully calibrated tuning forks to monitor the rotation rate of the air @-@ turbine @-@ powered mirror R , and he would typically measure displacements of the slit image on the order of 115 mm . His 1879 figure for the speed of light , 299944 ± 51 km / s , was within about 0 @.@ 05 % of the modern value . His 1926 repeat of the experiment incorporated still further refinements such as the use of polygonal prism @-@ shaped rotating mirrors (enabling a brighter image) having from eight through sixteen facets and a 22 mile baseline surveyed to fractional parts @-@ per @-@ million accuracy . His figure of 299 @,@ 796 ± 4 km / s was only about 4 km / s higher than the current accepted value . Michelson 's final 1931 attempt to measure the speed of light in vacuum was interrupted by his death . Although his experiment was completed posthumously by F. G. Pease and F. Pearson , various factors militated against a measurement of highest accuracy , including an earthquake which disturbed the baseline measurement .

= = = Relative speed of light measurements = = =

" Sur un système d 'expériences à l 'aide duquel la théorie de l 'émission et celle des ondes seront soumises à des épreuves décisives . " by F. Arago (1838)

Sur les vitesses relatives de la lumière dans l 'air et dans l 'eau / par Léon Foucault (1853)

" Sur l 'Experience relative a la vitesse comparative de la lumiere dans l 'air et dans l 'eau . " by H. Fizeau and L. Breguet (1850)

= = = Absolute speed of light measurements = = =

Sur une experience relative a la vitesse de propagation de la lumière by H. Fizeau (1849)

Mesure de la vitesse de la lumière ; Étude optique des surfaces / mémoires de Léon Foucault (1913)

Détermination de la vitesse de la lumière : d 'après des expériences exécutées en 1874 entre l 'Observatoire et Montlhéry , by M. A. Cornu (1876)

= = = Classroom demonstrations = = =

Speed of Light (The Foucault Method)

A modern Fizeau experiment for education and outreach purposes

Measuring the Speed of Light (video , Foucault method) BYU Physics & Astronomy