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The Newcomb-Michelson Velocity of Light Experiments

Introduction

In 1877, at age 42, Simon Newcomb became the Superintendent of the Nautical Almanac Office (NAO), U.S. Naval Observatory, in Washington D.C. That same year, at age 25, Ensign Albert Michelson began his new assignment as a professor of physics and chemistry at the U.S. Naval Academy, in Annapolis, Maryland [Reingold, 1964]. While they worked for the same agency, less than one hour by train apart, the two men lived in very different worlds. Newcomb had already achieved international acclaim for his studies of the orbits of Neptune and Uranus, and had his choice of any number of prestigious and powerful positions at scientific institutions and astronomic observatories throughout the nation. As a junior naval officer Michelson could, at best, expect to spend a few years teaching at the Academy before being re-assigned to sea duty. In the first two years after graduating from the Academy Michelson had already served aboard five ships of the line, sailing to ports as distant as Rio de Janeiro [Livingston, 1973].

Newcomb had direct access to the Secretary of the Navy and members of Congress, and when he learned that Michelson had began to work on velocity of light experiments, he did not hesitate in having the young Ensign detailed to the Naval Observatory. Together they assembled and perfected the apparatus to measure the velocity of light more accurately than it had ever been done before, and the value obtained from the complete set of experiments performed in Washington, 299,810 km per second, was not bettered for more than four decades.

Newcomb's and Michelson's Paths Cross

Newcomb entered science in 1861 as a computer for the NAO, and considered the work of determining the motions of the planets and stars required to create the nautical almanac *"to embody the highest intellectual power to which man had ever attained..."* [Newcomb, 1903]. The accuracy of predicting the motions of the planets was limited by the uncertainty of the distance from Earth to the Sun, known as the astronomical unit. In 1867 Newcomb suggested that experiments should be done to better determine the velocity of light, which was needed to improve the determination of the astronomical unit. For nearly a decade no American scientist stepped up to the challenge and Newcomb began to search the literature to learn about and evaluate the relative merits of techniques developed by researchers in other nations, with an eye toward taking on the task himself. He concluded that the method used by the French physicist Jean Bernard Leon Foucault (1819 – 1868) offered the most promise of success [Newcomb, 1883].

Foucault's method utilized a flat mirror, spinning on edge, to direct a beam of light, much as a lighthouse beacon, to a distant reflector [Jaffe, 1960]. Knowing the distance traveled by the light and the angular velocity of the rotating mirror, and by observing the deviation between the outgoing and returning light caused by the rotation of the mirror during the time required for the light to make the round trip, the velocity of light could be computed. Of course the rotating mirror had to rotate much more rapidly than a lighthouse. In fact, with line lengths of only a few kilometers the mirror had to rotate at a rate of at least two hundred revolutions per second to achieve a deviation between the transmitted and reflected light large enough to accurately determine the velocity of light.

Independently, in preparing his lectures Michelson also reviewed the recent determinations of the velocity of light, and concluded that Foucault's approach was the best thus far conceived. However, in studying the arrangement of the optical components it occurred to him that a simple change in the positioning of the rotating mirror and objective lens would allow the distance over which the light traveled to be greatly increased [Livingston, 1973]. The deviation between the transmitted and reflected light would be proportionally increased, which should dramatically improve the accuracy of the determination of the velocity of light. Michelson, perhaps because of his youth, threw any doubts aside and immediately launched into his experiments, using components from the Academy's physics laboratory and a mirror purchased with personal funds.

It is not clear exactly when and how Newcomb first learned of Michelson's experiments. Historical records include part of a letter (signature missing), dated March 25, 1878, and addressed to Newcomb, which described the results of a preliminary experiment [Livingston, 1973]. The letter contained such detailed information as the length of the line, size and rate of rotation of the mirror, and the deviation between the transmitted and reflected light. On April 26, 1878 Michelson himself wrote to Newcomb. After acknowledging that he had *"read in the 'Tribune' an extract of your paper on a method for finding the velocity of light*" Michelson went on to describe his own experiments, reporting that just as he *"was about to make an accurate observation the mirror flew out of its bearing and broke."* Newcomb was sufficiently impressed that he traveled to Annapolis to meet the young scientist and examine his apparatus. Afterward, Newcomb first encouraged the Navy to seek funding from Congress to support Michelson's work, but then presented his own proposal to the National Academy of Sciences, seeking help in convincing the Secretary of the Navy to request funding from Congress.

In March 1879, Congress appropriated $5,000 for the velocity of light experiments and Newcomb was directed to lead the effort. At Newcomb's request, Michelson was detailed to NAO to assist with the experiments [Newcomb, 1883]. It would be easy to question Newcomb's motives or actions, but there is little doubt that the chances of Congress funding the research were much better if it was to be done in Washington D. C., directly under his supervision, rather than in Annapolis by a relatively unknown junior naval officer. Figure 1.

Designing the Apparatus

Though Michelson had shown that a simple change in Foucault's optical design greatly increased the distance over which the return image could be observed, and therefore improved the accuracy with which the deviation of the beam could be measured, Newcomb did not modify his nearly completed design of the apparatus to be used for the Washington D. C. experiments (Figure 2). He felt that atmospheric conditions would limit the usable line length in any case, and focused on developing a reliable rotating mirror assembly, which he saw as a more immediate problem. Michelson had already suffered the setback of having his rotating mirror assembly fail under the stress of centrifugal force at 200 revolutions per second. Even if the mirror could be made strong enough to avoid such failure, the disk shaped single sided mirror used in Michelson's design wasted much of the returning light and created air turbulence in the optical path.

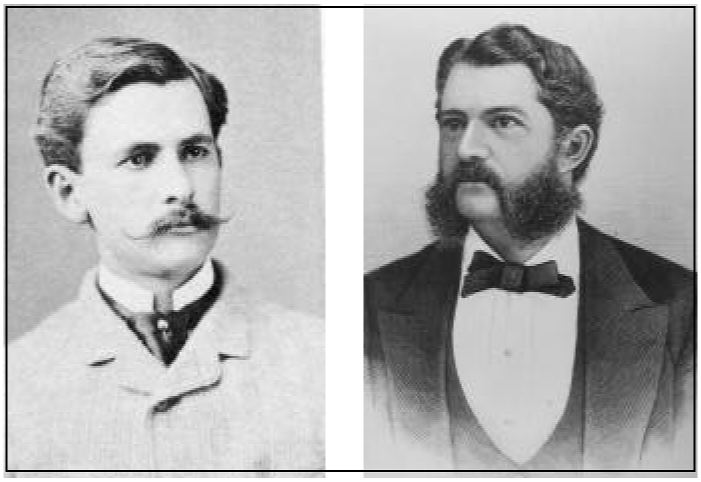

Fig. 1. These photographs of Simon Newcomb (right) and Albert Michelson were taken within a few years of the period when they jointly conducted experiments in Washington D.C to determine the velocity of light. Courtesy, U.S. Navy.

Newcomb [1883] credited Henry A Rowland, a colleague and professor of physics at Johns Hopkins University, with the idea of using a *"single piece of polished steel as the mirror, which could then be made of sufficient thickness to guard against lateral flexure."* From this seminal idea, Newcomb conceived the idea of replacing the flat mirror with a four sided steel prism, with each face polished. The design provided four times the light as Michelson's single sided mirror, and created much less air turbulence. The design was not without faults. The mass of mirror was much larger than any used before, which Newcomb worried *"would proportionately increase the friction which might be produced by any want of coincidence between the axis of inertia and that of rotation."* The resulting vibrations might well limit the maximum usable rate of rotation. The increased mass also made the method of driving the mirror more difficult. Newcomb ruled out the use of gears because they would wear quickly and might also introduce vibrations that would degrade the image. He also rejected a directly coupled electric motor, and decided to use an air turbine drive, similar to that used by Michelson.

Determining the rate of rotation of the mirror was another problem. Newcomb had used the combination of a break-circuit chronometer and chronograph in his astronomic observations and decided that the approach could be adapted to record the rotation of the mirror. This turned out to be a poor decision, because the mirror rotated about 12,000 times more rapidly than the chronograph. The chronograph was modified to rotate six times faster than normal, and a set of gears were used to reduce the number of pulses from the rotating mirror to one per 28 rotations. The gear system at first proved unreliable and required much reworking. Michelson had taken a very different approach to this problem. He placed a mirror, mounted on an electronically driven tuning fork, between the rotating mirror and the eyepiece. When the mirror was adjusted to rotate at the exact frequency of the tuning fork, the reflected image became sharp. Of course, the frequency of the tuning fork had to be carefully determined, and Michelson was assisted in doing so by Alfred Marshall Mayer, a professor at Stevens Institute of Technology, in Hoboken, New Jersey [Livingston, 1973].

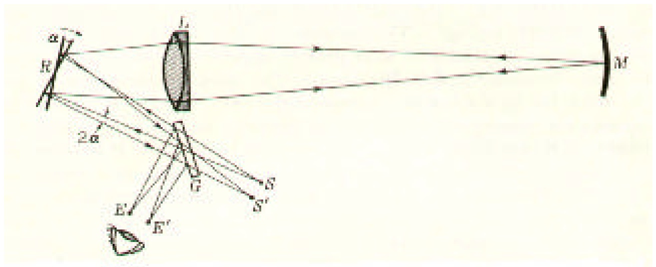

Fig.2. This simplified sketch shows the general layout of the optical components used for the Newcomb-Michelson Washington D.C. velocity of light experiments. S was the light source (illuminated slit), G was a beam splitter, R was the rotating mirror, L was the objective lens, M was a fixed spherical mirror, and E was the observer's eyepiece. The image returning from the fixed mirror was displaced by twice the angle through which R rotated during the time interval that it took for the light to travel from R to M. By measuring the angular velocity of R, the angular deviation 2 α, and the distance RM, it was possible to compute the velocity of light.

The Washington D.C. Experiments

Newcomb selected an elevated location on the Virginia side of the Potomac River, which commanded an excellent view of Washington D.C., to place the rotating mirror station (Figure 3). The site was on the grounds of Fort Whipple (later Fort Myer). Two sites were selected for fixed mirrors, one on the grounds of the Naval Observatory (Foggy Bottom) and the second near north-west corner of the Washington Monument. The former was 2,550.95 m and the later 3721.21 m from the Fort Whipple station, as determined by the U.S. Coast and Geodetic Survey (USC&GS). To accurately determine the distances, the USC&GS first established a few hundred meters long baseline on Analostan Island (now Roosevelt Island) in the Potomac River, using 4 meter long agate capped steel slide-rods. Triangulation was then used to extend a network to each of the reflector stations.

Michelson participated in the Washington D.C. observations until September 1880, when he was granted a leave of absence by the Navy to study in Europe. Newcomb continued the experiments for two more years. In his final report [Newcomb, 1883] he gave two values for the velocity of light in vacuum. First, a value of 299,860 km/sec based only on observations made in 1882, which he preferred because he thought that they were less affected by systematic errors. Second, 299,810 km/sec based on a weighted combination of all the observations, which proved to be the more accurate value.

Newcomb's report also included several suggestions for future experiments: Michelson's optical design should be used; the rotating mirror should have more faces (at least 5) and should be designed to rotate at 500 revolutions per second, or more; and much longer lines should be used. To achieve the last recommendation he pointed out that: *"In the Rocky Mountains or the Sierra Nevada no difficulty would be found in finding stations at which a return ray could be received from a distance of 30, 40, or even 50 kilometers, with little more dispersion and loss than at a distance of 4 kilometers through the air of less favored regions."*

More than 40 years later, from1924 to 1927, Michelson fulfilled Newcomb's vision by measuring the velocity of light over a 35 kilometer line between the Mt. Wilson Observatory and Mount San Antonio, in the San Gabriel Mountains of California. The rotating mirror had eight faces, and was made of steel to withstand the centrifugal force at 528 rev/sec. Michelson obtained a value of for the velocity of light in vacuum of 299,798 ± 4 k/sec, compared to the value of 299,792.458 k/sec accepted today.

Concluding Remarks

For Simon Newcomb and Albert Michelson any initial unease related to their differences in age, position and past achievements were quickly dispelled by their commitment to obtaining the best possible measurement of the velocity of light. They worked together for only a matter of months, but continued to communicate and share their ideas for many years thereafter. Experiments performed by Michelson two decades after Newcomb's death still used techniques and instrument designs originated by Newcomb. History books do not record it as so, but Michelson's Mt. Wilson experiment might more rightly be considered the conclusion of the Newcomb-Michelson velocity of light experiments begun in Washington D.C., more than four decades earlier.

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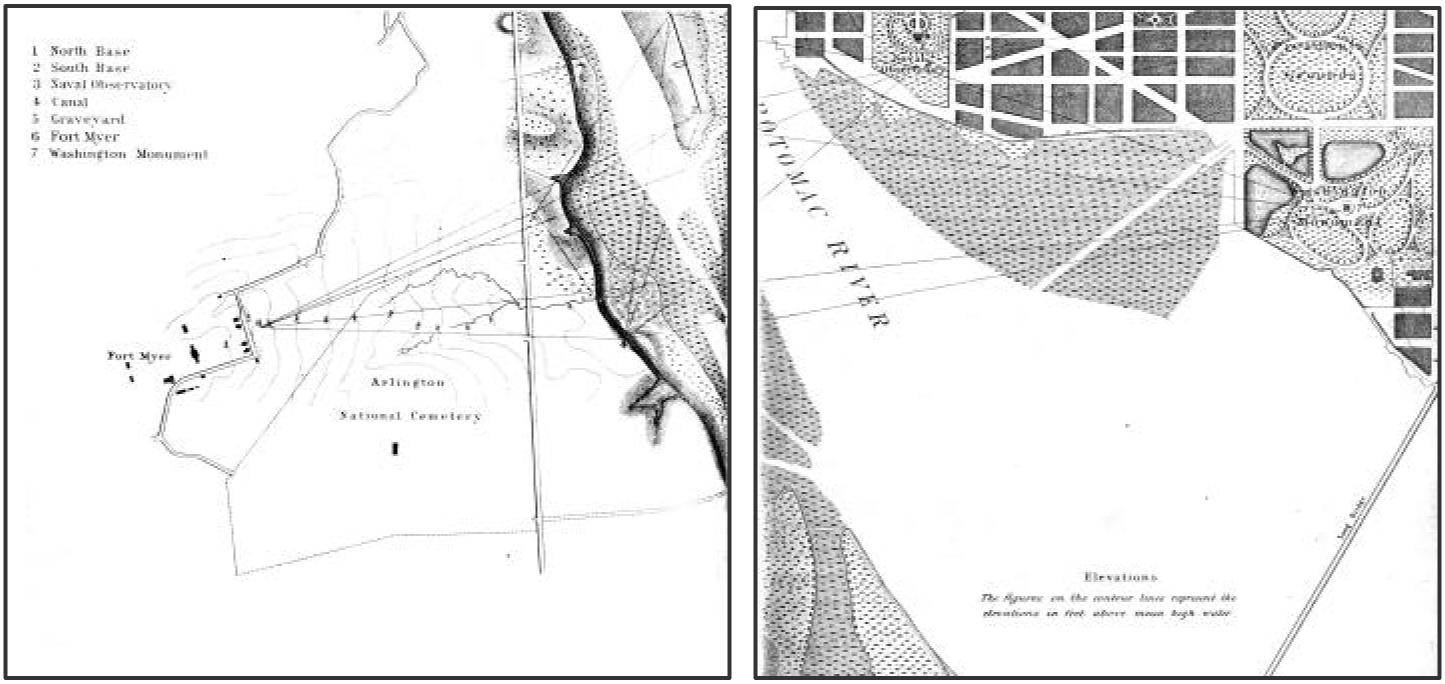

Fig. 3. This two-plate map, copied from Newcomb [1883], shows the locations of the stations used in the Newcomb - Michelson Washington D.C. velocity of light experiments. The lines between points near Fort Meyer, the Naval Observatory, the Washington Monument, the ends of the baseline on Analostan Island, and other points, represent the triangulation network established by the Coast and Geodetic Survey to accurately determine the distances traveled by the light.