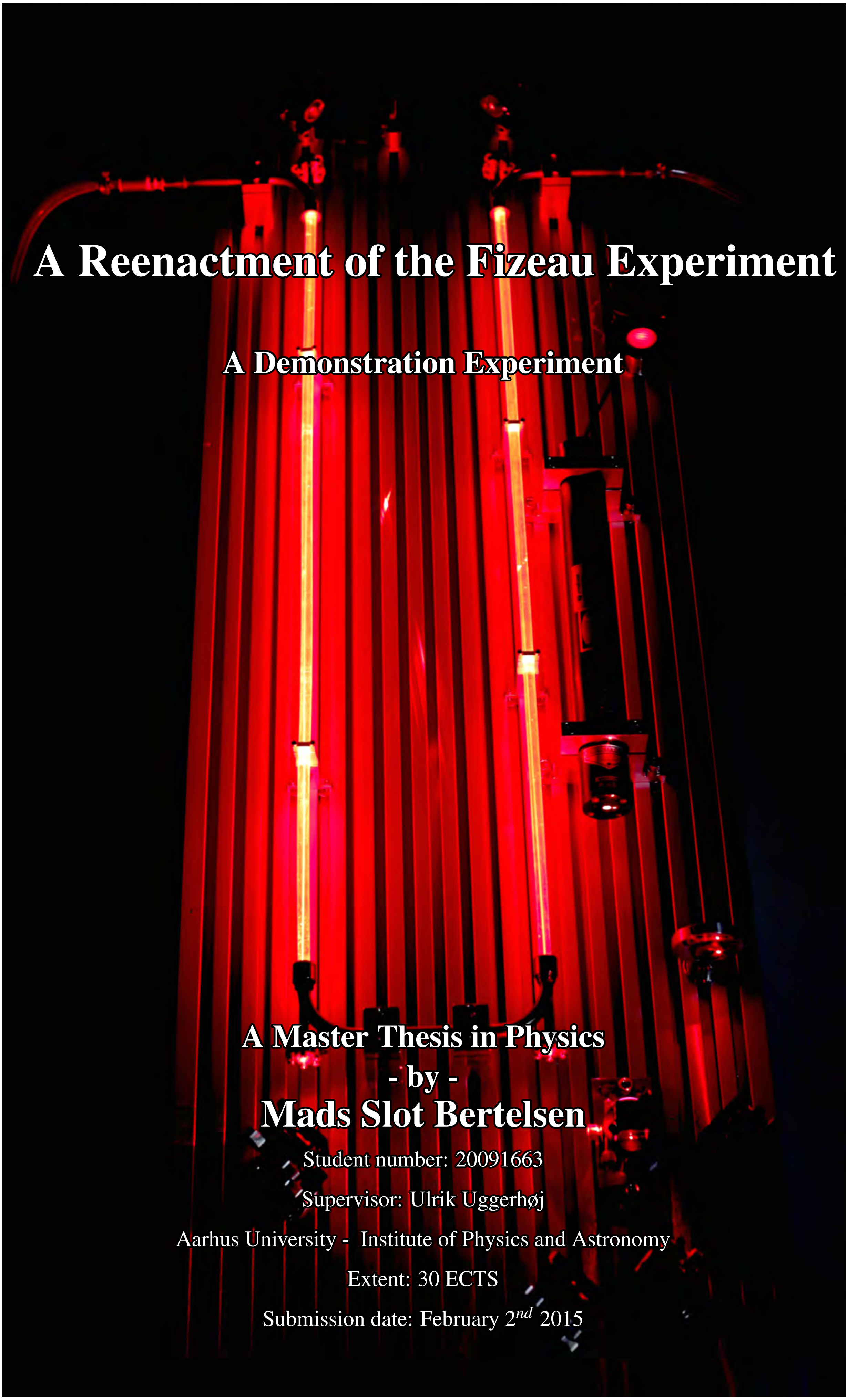

A Reenactment of the Fizeau Experiment

A Demonstration Experiment

A Master Thesis in Physics

- by -

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Abstract

In 1851 french physicist Fizeau preformed an experiment that aimed to test the properties of aether drag. Little did he know that his experiment would influence the world of physics throughout the century and over the turn of the 20$^{\text{th}}$ century. He ended up confirming the theory of partial aether drag by Fresnel even though this theory was later rejected. A new theory had to account for Fizeau's measurements and Lorentz did just that by introducing the concept of local time into his theory of electrons. Lorentz's work inspired Einstein in his development of the special theory of relativity and he later stated that "[...] the experimental result which had influenced him the most were the observations of stellar aberration an Fizeau's measurements..."[1]. This way Fizeau's aether drag experiment came to be known as a relativistic experiment performed 50 years before the theory of relativity emerged.

This thesis contains a description of the work done on a 10 year old setup of the Fizeau experiment. The setup had never been functional before yours truly got to work on it and after doing some modifications in terms of reducing unnecessary vibrations and introducing a new water flow control, it came to give some reasonable results. Further improvements to the setup is suggested and once these have been implemented I believe the setup will deliver beautiful results.

This take on the Fizeau experiment was designed as a demonstration experiment and it does just that quite well, as it is both visually appealing but also makes it possible to see the special theory of relativity unfold in front of your eyes.

The Fizeau experiment is quite ingenious in it's simplicity and wondrous in it's application and I believe this modern take on the experiment reflects those standards.

[1] [18] pp. 48, line 31-33.

Contents

1

Introduction

On the sides of the Eiffel Tower some of the most influential French scientist's names are engraved. Among them we count Fourier, Coulomb, Fresnel, Lagrange, Laplace and Fizeau. One of the reasons Fizeau clearly deserves a place in this impressive company are his contributions to the world of physics, which would highly influence the scientific community in the second part of the 19th century. Fizeau's famous aether drag experiment proved Fresnel's theory of partially dragged aether, which came to be a great mystery as later experiments was not successful in detecting the properties of aether. Fizeau's result could however not be ignored and it ended up playing a role in the development of the special theory of relativity. Albert Einstein himself stated, in an interview with Robert Shankland in 1950, that "[...] the experimental result which had influenced him the most were the observations of stellar aberration an Fizeau's measurements..."[2]

In this thesis I aim to clarify how the measurements of Fizeau played a role in the development of Einsteins special theory of relativity by looking at how the Fizeau experiment came to be, and how it influenced the field of Physics throughout the century and until the special theory of relativity emerged. How did an experiment which confirmed the presence of aether came to inspire a theory which reject it's mere existence.

A decade ago the construction of a reenactment of Fizeau's experiment began at Aarhus University. The setup was designed to be a demonstration experiment which could be transported into an auditorium or a class room. The setup however never came to function in spite of numerous tries. The main focus of this thesis will be to get the experiment in working order, both as a mobile setup and as a functional experiment.

The reason for this reenactment of Fizeau's work is the potential simplicity of the setup, hence the possible didactic advantages. Relativistic experiments is often time consuming and feature large and complicated equipment. The straightforwardness of the direct implication of the velocity transformation, of the theory explaining this experiment, makes the experiment unique in understanding the time and space nature of the special theory of relativity. There is no need to understand cosmic decay or how photons interact with

[2][18] pp. 48, line 31-33.

matter in order for this setup to make sense.

The following thesis will thus contain a brief historical overview of Fizeau's motivation for performing the experiment and an explanation of how his experiment came to influence the development of the special theory of relativity. The main part of the thesis will contain a report on how I made the setup functional and on the execution of the experiment. I will furthermore shortly discuss the didactic possibilities of the setup, provide a shopping list for a simple reconstruction of the experiment and make a set of videos presenting the principle of the setup and a short historical introduction to the Fizeau experiment.

2

The History of the Aether Drag Experiment

The journey to the only aether experiment with a positive result starts in 1810 when Dominique Francois Jean Arago set out to find the differences in the speed of light. This would be the beginning of the downfall of the theory of luminiferous aether even though the experiment inspired the partial aether drag hypothesis of Augustin-Jean Fresnel (1818) which was later experimentally confirmed by Hippolyte Fizeau (1851). Albert Einstein was later inspired by the positive result of Fizeau's measurements in his development of the special theory of relativity.

2.1 Prologue - The Luminiferous Aether and Partial Aether Drag

In the end of the 19th century it was believed among scientist that luminiferous aether was the medium in which light was propagating. Aether was a material that was omnipresent throughout the universe and was the carrier of light from our sun and distant stars to the earth. The aether embraced the earth and was present all around us and in all materials. One of the people responsible of keeping the theory of luminiferous aether alive was the french scientist Augustin-Jean Fresnel, who postulated that aether was partially dragged along by matter as opposed to being fully entrained within it. Fresnel's partial aether drag theory was devised when he tried to explain the null result in fellow french scientist Dominique Francois Jean Arago's experiment of 1810. Arago did not set out to test the properties of aether but argued within the framework of the corpuscular theory of light. The corpuscular model was developed largely by Isaac Newton and was a theory which argued that light consisted of particles of different sizes and colors that was transmitted in a beam from a source. The speed of the light would then be dependent on the speed of the source (emission theory) and the speed of the observer. Arago argued that when observing the light from different stars he would be able to se different speeds of light.

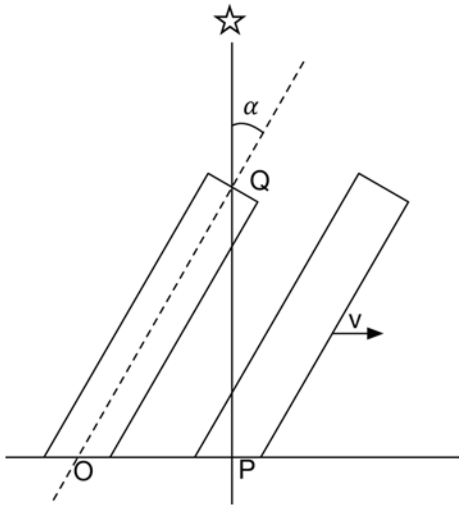


Figure 1: Stellar aberration with a hollow pipe telescope.

Using Snell's law;

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2},$$

he would be able to detect the difference in the speed of light through dispersing of the light through a prism. He mounted a prism on a telescope and observed different stars, two different days expecting also to see a difference from one day to the other, since earth's movement through space would influence the observed light speed. Arago however fail to see a difference in the speed of light.[3]

In 1818 Fresnel wrote a letter to Arago explaining the null result by introducing a modification to the immobile aether theory. The theory of immobile aether set the aether to be stationary throughout the universe thereby making the earth and everything on it move through the aether with the speed of earths velocity through space. The physics behind Fresnel's modification can be explained by looking at stellar aberration using two types of "telescopes". Stellar aberration is the phenomenon of stars not being in the location we see by looking directly at the heavens. In Figure 1 we observe a telescope consisting of a hollow pipe that moves through the immobile aether, with a speed of v, and a beam of light from a distant star propagating through the aether. Because of the telescopes movement it has to be tilted to an angle (α) in order for the light not to hit the sides of the telescope. The tilt is called the aberration angle and makes it possible for the light to

[3] [5]

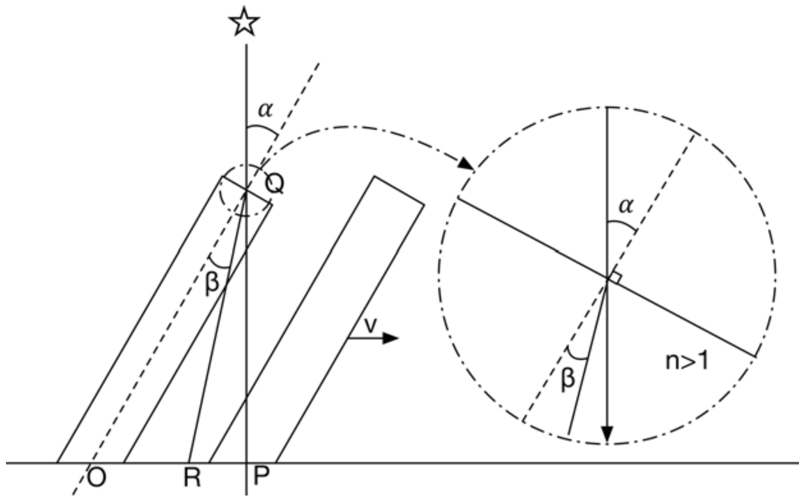


Figure 2: Stellar aberration with a glass cylinder telescope.

travel from entry of the telescope (point Q) to the base (point P). The aberration angle therefore has to be taken in to account when determining the location of objects in the sky. From Figure 1 one easily sees that $\tan\alpha = \frac{|OP|}{|PQ|}$ and by construction of the setup we also have $\tan\alpha = \frac{v}{c}$.

If the the hollow pipe telescope is replace by a cylinder consisting of a transparent material we would expect to see some form of refraction when the light enters the cylinder, resulting in a different aberration angle. Observations however show that there is no change in aberration angle which the theory of Fresnel should explain. In Figure 2 the new scenario of the transparent cylinder is illustrated. When we zoom in on the entrance of the telescope the new trajectory of the beam of light is set at an angle β according to the normal (the dotted line). If the refractive index outside the cylinder is set to be $n_0 = 1$ and the refractive index inside the cylinder is n, then Snell's law predicts $\frac{\sin(\alpha)}{\sin(\beta)} = n$. The angle of the telescope in Figure 1 and Figure 2 are highly exaggerated and in reality the aberration angle is quite small which makes it okay for us to change sinus to tangent. By the same argument we can assume that the lines $|OR|$ and $|QR|$ are perpendicular then giving us: $\sin(\beta) \approx \tan(\beta) \approx \frac{|OR|}{|QR|}$. If $\Delta t = |QP|/c$, being the time it takes for the light to travel the distance $|QP|$, we then write the the following lines as: $|OP| = v\Delta t$, $|RP| = fv\Delta t$ and $|QR| = \frac{c}{n}\Delta t$ (the speed of light through the transparent material is reduced by n). Using the above we get:

$$\tan(\alpha) \approx n \cdot \tan(\beta) \approx n\frac{|OR|}{|QR|} = n\frac{|OP|-|RP|}{|QR|} = n\frac{v\Delta t - fv\Delta t}{\frac{c}{n}\Delta t} = n^2(1-f)\frac{v}{c}.$$

Seeing as $\tan(\alpha) = \frac{v}{c}$, the only way we get $\alpha = \beta$ is when $n^2(1-f) = 1$. Hereby we get the Fresnel dragging coefficient $f = 1 - \frac{1}{n^2}$.

The above derivation is only valid in the frame of the aether because the impact angle of the beam, in the frame of a terrestrial observer, would be perpendicular to the telescope entrance, hence not giving cause to refraction.[4]

2.2 The Fizeau Experiment

In 1851 Fizeau managed to observe the partial aether drag predicted by Fresnel[5]. After 30 years of scientist failing to observe this effect, Fizeau succeeded in designing an experiment that used beams of light through moving water to observe partial aether drag. The setup Fizeau devised consisted of two parallel tubes that would contain flowing water or air. At the end of each tube a transparent window was placed allowing a beam of light to enter the pipes. Fizeau did not publish a drawing of the setup in his article but a sketch made by Janssen/Stachel [9] can be found in Figure 3. Because the speed of light is so much greater than the speeds which water and air can be pushed through such a tube, Fizeau used an interferometer to measure any changes. Fizeau ascribed the invention of the interferometer to Arago:

> We owe to Arago a method of observing, founded on the phenomena of interference, which is well suited to render evident [...] the least change in the velocity with which the body is traversed by light...[6]

As a light source he used the light of the sun which was guided onto a transparent mirror (beamsplitter), afterwards the beam was put through a convergent lens which was designed to make the path of the light parallel to the tubes. The beam then reach a screen

[4] [9] Page 9-11.
[5] This section is written on the basis of the translation of Fizeau's original article from 1851 [7].
[6] [7] Page 2, line. 5-8.

with two holes in it, allowing each resulting beam to travel trough its own tube. Upon exiting the tube the beams was refocussed by another lens onto a mirror that sent the beams back through the other tube. After the beams traveled their different ways through the system they would be rejoined and generate an interference pattern which would be observed by a graduated eye-piece.

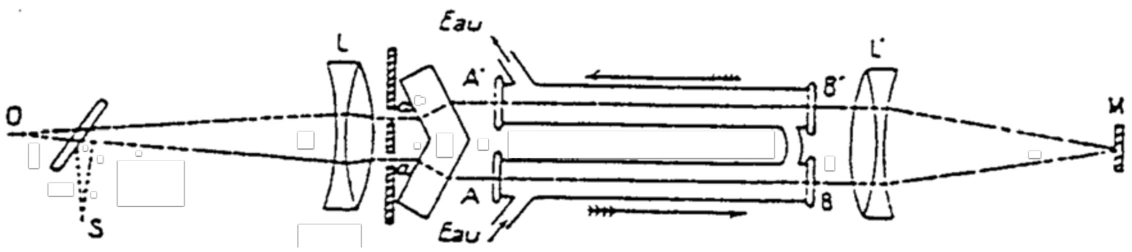


Figure 3: Sketch of Fizeau's setup.[7]

Fizeau expected his experiment to show one of three possibilities:

1. The aether completely moves with the body, hence the speed of light are ether increased or decreased by the speed of the body. (This corresponds to the theory of fully entrained aether by George Stokes)

2. The aether is not influenced by the movement of the body, hence no variation in the speed of light will occur.

3. The aether is carried partially by the body ether increasing or decreasing the speed of light by a fraction of the speed of the body. (This corresponds to the partial aether drag hypothesis of Fresnel)

He then went on to say; "The question then resolves itself to that of determining with accuracy the effect of the motion of a body upon the velocity with which light traverses it."[8], thereby stating that his experiment would yield the correct of the above possibilities. The setup did not return a positive result for air but gave cause to a shift in interference band of $\Delta\phi_{exp} = 0.23016$, nearly a fourth of the breadth of a band, at water flow velocity $u = 7.059m/s$. Fizeau's theoretical derivations of the band shift corresponding to the aether theory of Stokes and Fresnel is undergone in section 3.1.1 and section 3.2.1,

[7][9] Page 13

[8][7] Page 1, line 30-31.

respectively. He found that light at wavelength $\lambda = 526$nm appeared to maintain the greatest intensity after traveling through the setup. The theoretical interference band shift was then calculated to be $\Delta\phi_{Stokes} = 0.4597$ for the theory of fully entrained aether and $\Delta\phi_{Fresnel} = 0.2022$ for the partial aether drag theory. Fizeau assigns the difference between $\Delta\phi_{exp}$ and $\Delta\phi_{Fresnel}$ to be caused by an error in estimating the velocity of the water. The velocity of the water was calculated as a mean velocity which Fizeau realized was not indicative for the velocity of the water the light moved through. Because of drag at the sides of the pipes the water is bound to move quicker towards the middle of the pipe, where the light beams are, thus the water flow velocity is greater than first assumed causing the calculated interference band shift to be too low. Fizeau argues that the correct value of $\Delta\phi_{Fresnel}$ should be around 0.23 hence concluding:

> Thus the displacement of the bands caused by the motion of water, as well as the magnitude of this displacement, may be explained in satisfactory manner by means of the theory of Fresnel.[9]

He concludes his 1851 article by stating his experiment as a succes;

> The succes of this experiment must, I think, lead to the adoption of the hypothesis of Fresnel...[10],

but also notes that he does not presume to think that the matter of aether is exhausted:

> ...to many the conception of Fresnel will doubtless still appear both extraordinary and, in some respects, improbable...[11]

2.3 Lorentz's Electron Theory and the Beginning of the Special Theory of Relativity

The next leap in the development of an aether theory was Lorentz's development of his electron theory in which he suggested a total immobile aether and furthermore an abso-

[9] [7] Page 7, line 38-39.
[10] [7] Page 9, line 25.
[11] [7] Page 9, line 25.

lute separation between aether and matter. Lorentz's theory of electrons, developed in the 1890's, proposed that aether and matter was completely separated and could only interact through tiny particles which he later called electrons. The theory set out to explain both electromagnetic and optical phenomenon, in bodies in rest and in motion, through the electromagnetic theory of James Clerk Maxwell. In suggesting an immobile aether Lorentz then had to explain the numerous null results in detecting earths movement according to this stationary aether, including the famous Michelson-Morley experiment, and of course also explain the result of the Fizeau experiment. He therefore had to explain the Fresnel dragging coefficient by means of his new theory without introducing any aether drag. Lorentz managed to show that the electromagnetic waves, and not the aether, was partially dragged along in the medium of which it propagated. When dealing with physical systems moving through an immobile aether Lorentz introduced a set of auxiliary quantities which made it possible to use the same equations as usual when dealing with light propagation in a moving body. One of these auxiliary quantities was introduced as 'local time' t' and could be expressed according to ordinary time t as follows;

$$t' = t - \frac{V}{c^2} \cdot x, \tag{1}$$

for a system moving along an x-axis with a speed V according to the immobile aether. Lorentz then used the principle of 'local time' to derive the dragging coefficient of Fresnel. When describing a wave moving along the x-axis in a medium at rest in an immobile aether, one could express this via a sinusoidal wave:

$$f(x,t) = A \cdot \cos\left(\frac{\omega}{v'}(x - v't) + \delta\right).$$

A being the amplitude of the wave, ω the anger frequency, v' the speed og the wave in the medium and δ the phase constant. If one were to simplify this expression by ascribing $\omega = -1$ and $\delta = 0$ the phase of the wave is then expressed by: $\frac{-1}{v'}(x - v't) = t - \frac{x}{v'}$ and since the speed og light in a medium is $\frac{c}{n}$, n being the refractive index of the medium and c the speed of light in vacuum, we get the phase of the wave: $t - \frac{x}{c/n}$. If the medium were to move through the aether at a velocity of V along the x-axis the phase should now be expressed using local time: $t' - \frac{x}{c/n}$. Thus using equation (1) one gets:

$$t' - \frac{x}{c/n} = t - \frac{V}{c^2}x - \frac{x}{c/n} = t - \left(\frac{V}{c^2} - \frac{n}{c}\right)x$$

and the speed of the wave according to the medium in ordinary time must be:

$$\hat{v} = \frac{1}{\frac{V}{c^2} - \frac{n}{c}} = \frac{c}{n} \cdot \frac{1}{\frac{V}{nc} + 1}.$$

For $V << cn \Leftrightarrow \frac{V}{cn} << 1$, one uses the first order Taylor approximation[12]:

$$\hat{v} = \frac{c}{n} \cdot \frac{1}{\frac{V}{nc} + 1} = \frac{c}{n}\left(1 - \frac{V}{nc}\right) = \frac{c}{n} - \frac{V}{n^2}$$

and then get the velocity of the light wave according to the aether:

$$v = \hat{v} + V = \frac{c}{n} - \frac{V}{n^2} + V = \frac{c}{n} + \left(1 - \frac{1}{n^2}\right)V.$$

This is the Fresnel dragging coefficient $f = 1 - \frac{1}{n^2}$ explained without the use of the concept of aether drag.[13] In 1895 Lorentz postulated his hypothesis of length contraction (earlier suggested by FitzGerald in 1889) to explain the Michelson-Morley experiment. The hypothesis stated that an object contracts in the direction of movement through aether with a factor of $\sqrt{1 - \frac{v^2}{c^2}} = \gamma^{-1}$. γ would later be named the Lorentz factor.[14]

2.4 The Role of the Fizeau Experiment in the Development of the Special Theory of Relativity

The development of the special theory of relativity has in many years been surrounded by great awe and astonishment and with good reason. In the year 1905 Albert Einstein wrote his four Annus mirabilis (miracle year) papers which would end up changing our understanding of the world around us and would contribute significantly to the foundation of modern physics. At the time Einstein worked at the Patent Office in Bern and not at an academic position which would be expected of a man who would have such great impact on the world of science. The story of the man who worked at a patent office while changing the world of science became widely known and also surrounded by several myths. The most famous of the papers is the one concerning the relativity principle

[12] explained shortly in section 3.2.3

[13] [9] Page 22-25.

[14] For an in depth clarification of Lorentz's reasoning to explain the Michelson-Morley experiment see [9] page 25-32.

entitled ”On the electrodynamics of moving bodies”. The title itself can seem curious to the modern reader since the special theory of relativity is a theory of time and space, I will return to the discussion about this oddity later. One of the greatest myths concerning Einstein and the development of special relativity is that he by a single stroke of genius discovered the theory, another is that a few experiments (Fizeau’s aether drag experiment and the Michelson-Morley experiment among others) inspired him in the development. Historian Oliver Darrigol argues that these myths must not be believed: ”A conscientious historian cannot trust such myths, even thought they may contain a grain of truth.”[15]. But how did these myths come to be, specifically the last one concerning Fizeau’s experiment? And what part of the myth is the grain that is true?
In the period 1950-1954 american physicist and historian Robert S. Shankland visited Einstein in Princeton for a series of five conversations which Shankland wrote down shortly after each visit. The writings was originally meant to serve as a private record but was later published. At the first meeting they talked about both the Michelson-Morley experiment and the Fizeau experiment. Shankland writes:

> When I asked him how he had learned of the Michelson-Morley experiment, he told me that he had become aware of it through the writings of H. A. Lorentz, but *only after 1905* had it come to his attention! ”Otherwise” he said ”I would have mentioned it in my paper.” He continued to say the experimental result which had influenced him most were the observations of stellar aberration and Fizeau’s measurements on the speed of light in moving water. ”They were enough,” he said.[16]

It has later been questioned whether Einstein in fact did know about the Michelson-Morley experiment.[17] But more interestingly when Einstein says he would have mentioned the Michelson-Morley experiment if he had known about it, why did he not mention the Fizeau experiment which he actually knows about? A paragraph in Einstein’s 1905 article treat stellar aberration so why does he not treat the Fizeau experiment as well?

[15][1] Page 1, line 24-25.
[16][18] Page 48, line 25-35.
[17]For more on this subject: [1]

28 year before on December 14th 1922 Einstein gave a lecture in Kyoto under the title "How I created the theory of relativity". The talk was given in German and translated and written down in Japanese later to be translated into English. At the lecture Einstein mentions Fizeau when talking about the work of Lorentz:

> Then I tried to discuss the Fizeau experiment [...] as originally discussed by Lorentz.[18]

It is evident that Einstein was familiar with and influenced by the Fizeau experiment.

To understand why Einstein does not mention Fizeau in his paper one must take a closer look at the article and the time it was written. In the turn of the century the electrodynamics of moving bodies was a hot topic in the scientific community. Several articles and experiments was dedicated to the topic of electrodynamics of moving bodies. Some of the greatest physicist of the time worked on the topic, among them was: Hendrik Lorentz, Henri Poincaré and Alfred Bucherer.[19] The great interest of the time explains that Einstein's focus of the paper was electrodynamics and the title came to be: "On the Electrodynamics of Moving Bodies".

The paper consists of two parts, one named "Kinematic Part" the other named "Electrodynamic part". In the introduction he explains that the notion of aether is superflous and explains the intent of the article is to solve contradictions in the theories of electrodynamics of moving bodies. In the kinematical part he states the two postulates which is the base of the special theory of relativity:

1. The laws governing the changes of the state of any physical system do not depend on which one of two coordinate systems in uniform translational motion relative to each other these changes of the state are referred to.

2. Each ray of light moves in the coordinate system "at rest" with the definite velocity c independent of wether this ray of light is emitted by a

[18] [4]
[19] [1] Page 1

body at rest or a body in motion.[20]

He furthermore defines time synchronicity, shows simultaneity is a relative notion, derives the Lorentz transformations, introduces length contraction and introduce the relativistic velocity transformation:[21]

$$v = \frac{v' + V}{1 + \frac{v'V}{c^2}}.$$

In the electrodynamic part he then uses the results of the kinematic part to solve some of the physical problems of the time concerning electrodynamics in moving bodies. More specifically in §7 of the paper he derives stellar aberration. To the modern reader it can seem surprising that Einstein did not use the velocity transformation to derive both stellar aberration and explain the result of the Fizeau experiment. As historian John Norton puts it:

> It might seem surprising that Einstein could devise and publish the relativistic rule of velocity composition in his 1905 paper (§5) without recognizing that the result of the Fizeau experiment is a vivid implementation of the rule. [...] Yet Einstein (1905, §7) derives the result from the same transformation of the waveform that gives the Doppler shift without mention of velocity composition.[22]

As implied in the above quote from Kyoto, Stachel further interprets:

> Even Einstein was still so much under the spell of Lorentz's interpretation that he failed to notice the kinematic nature of Fresnel's formula...[23]

The Fresnel formula was not derived, using the velocity transformation, until physicist Max von Laue did it in 1907.[24]

[20] [3] Page 143, line 22-27. I have changed the notation on the speed of light from V to c to be consistent in notation.

[21] The notation is borrowed from section 3.2.1

[22] [15] Page 49, line 12-14 + 18-19.

[23] [20] Page 10, line 31-32.

[24] [12]

In 1905 Einstein wrote the article which would earn him the title as the father of the theory of relativity. In the paper there is no references to previous work by him or other scientists which have spun myths and interested historians for a long time. Historian Darrigol stress that Einstein was not solely responsible for the theory of relativity: "... Einstein was neither the first nor the last contributor to relative theory."[25] Never the less there is no denying that the paper marked a dramatic step in how we perceive the world of physics and the world in generel. As Einstein mentions, to Shankland in 1950, the Fizeau experiment influenced him a lot in the development of the special theory of relativity, probably largely through Lorentz's electron theory of which the work of Fizeau's played a large part. Even the title of Fizeau's 1851 paper "On the Effect of the Motion of a Body upon the Velocity with which it is traversed by Light" seems as a breadcrumb which leads to Einstein's paper: "On the Electrodynamics of Moving Bodies".

[25] [1] Page 22, line 12.

3

Theory

3.1 Classical Theory

The following section covers Fizeau's original deduction which results in the non-relativistic fully entrained aether formula:

$$\Delta\phi = 4l\frac{1}{\lambda}\frac{u}{c}n^2$$

3.1.1 Fizeau's "Classical" Formula

While this section maybe called "Fizeau's Classical Formula" it in reality should be called "Fizeau's Formula for Completely Dragged Aether", because he devised the formula for an aether which is fully dragged by the water in his setup. Never the less the section got the above name because the formula is the same as derived by classical emission theory. Let c be the speed of light in vacuum, v_0 be the speed of light in water, $n = \frac{c}{v_0}$ be the refractive index of water and u be the speed of the water. When light moves in the same direction as the water the total speed of the light must be $v_0 + u$ because the aether is completely dragged along by the water. By the same argument the speed of light, when moving against the water, must be $v_0 - u$. Fizeau then describes the length difference travelled by the light which moves along the water versus against the water:

$$\Delta = L\left(\frac{c}{v_0 - u} - \frac{c}{v_0 + u}\right).$$

Δ being defined as the required retardation by Fizeau while L is the length the light travels trough water. He the goes on and reduces the above expression:

$$\Delta = L\left(\frac{c}{v_0 - u} - \frac{c}{v_0 + u}\right) = L\left(\frac{2cu}{v_0^2 + u^2}\right) = 2L\frac{u}{c}\left(\frac{c^2}{v_0^2 + u^2}\right) \approx 2L\frac{u}{c}\left(\frac{c^2}{v_0^2}\right), \quad \text{for } u << v_0$$
$$= 2L\frac{u}{c}n^2.$$

Δ is an expression for the difference in path of the two light beams, which can be converted to the displacement in interference bands by dividing by the wavelength of the light λ. The path of the beams can be rewritten; $L = 2l$, l being the length of the pipes used in the setup. Now we get the desired formula[26]:

$$\Delta\phi = \frac{\Delta}{\lambda} = 4l\frac{1}{\lambda}\frac{u}{c}n^2.$$

3.2 Relativistic Theory

The following section covers three deductions which results in the relativistic formula of Fizeau's aether drag experiment:

$$\Delta\phi = 4L\frac{1}{\lambda}\frac{u}{c}(n^2-1)$$

3.2.1 Fizeau's "Relativistic" Formula

Obviously Fizeau did not make a relativistic formula but his result for the calculations on partially dragged aether never the less, resultet in a formula which later was found to be consistent with special relativity.
Fizeau used the work of Fresnel to derive the formula for light in water partially dragged along by aether. Fresnel had the idea that the reason for light to move slower in water is because the density of aether within water is greater than in vacuum. Fizeau then writes an equation for two similar media that only differ in density;

$$\frac{\rho'}{\rho} = \frac{v^2}{v'^2},$$

which I rewrite in the following notation: $\frac{\rho'}{\rho} = \frac{c^2}{v_0^2}$. We now write:

$$\begin{aligned}\rho' - \rho &= \rho\frac{c^2}{v_0^2} - \rho'\frac{v_0^2}{c^2} = \rho\frac{c^2}{v_0^2} - \rho\frac{c^2}{v_0^2}\frac{v_0^2}{c^2} = \rho\left(\frac{c^2}{v_0^2} - 1\right)\\ &= \rho\frac{c^2 - v_0^2}{v_0^2}.\end{aligned}$$

By the idea of partial aether drag only some of the aether is dragged along by the water. The density of this aether is $\rho' - \rho$ and the density of the aether left behind at rest is ρ. To calculate the speed of the light in moving water Fizeau now consult Fresnel; "Fresnel considers that the velocity with which the waves are propagated then becomes increased

[26][7] Page 4-5.

by the velocity of the centre of gravity of the stationary and moving portions of æther."[27], thereby getting the formula for the change in speed of light in the moving water:

$$\frac{\rho' - \rho}{\rho'} u.$$

By the formulas above we get:

$$\frac{\rho' - \rho}{\rho'} u = \frac{(c^2 - v_0^2) v_0^2}{c^2 v_0^2} u = \frac{c^2 - v_0^2}{c^2} u.$$

Now the speed of light in a moving medium can be written as;

$$v^+ = v_0 + \frac{c^2 - v_0^2}{c^2} u \quad \text{and} \quad v^- = v_0 - \frac{c^2 - v_0^2}{c^2} u, \tag{2}$$

when light moves along or against the flow, respectively. As in Fizeau's "classical" derivation we now get an expression for the retardation:

$$\begin{aligned}
\Delta &= L \left(\frac{v_0}{v_0 - \frac{c^2 - v_0^2}{c^2} u} - \frac{v_0}{v_0 + \frac{c^2 - v_0^2}{c^2} u} \right) \\
&= L \frac{c\left(v_0 + \frac{c^2 - v_0^2}{c^2} u\right) - c\left(v_0 - \frac{c^2 - v_0^2}{c^2} u\right)}{v_0^2 - u^2 \left(\frac{c^2 - v_0^2}{c^2}\right)^2} \\
&= L \frac{\frac{c^2 - v_0^2}{c} u + \frac{c^2 - v_0^2}{c} u}{v_0^2 - u^2 \left(\frac{c^2 - v_0^2}{c^2}\right)^2} \\
&= 2L \frac{u}{c} \frac{c^2 - v_0^2}{v_0^2 - u^2 \left(\frac{c^2 - v_0^2}{c^2}\right)^2} \\
&\approx 2L \frac{u}{c} \frac{c^2 - v_0^2}{v_0^2}, \quad \text{for} \quad u << c \\
&= 2L \frac{u}{c} \left(\frac{c^2}{v_0^2} - 1 \right) \\
&= 2L \frac{u}{c} \left(n^2 - 1 \right), \quad n = \frac{c}{v_0} \text{ being the refractive index.}
\end{aligned}$$

We get the displacement of interference bands by dividing by the wavelength of the light λ:

$$\Delta\phi = \frac{\Delta}{\lambda} = 2L \frac{1}{\lambda} \frac{u}{c} \left(n^2 - 1 \right)$$

[27] [7] Page 6, line 14-15

3.2.2 Electrodynamic Interpretation

To treat the Fizeau problem, of light traveling trough moving water, with the theory of electrodynamics we start by looking at the Maxwell equations for moving media of a non charged and current free dielectric (since this is the properties of our water):

$$\nabla \cdot \mathbf{D} = 0 \qquad (1)^{28}$$

$$\nabla \cdot \mathbf{B} = 0 \qquad (2)$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \qquad (3)$$

$$\nabla \times (\mathbf{B} - \mu_0 \mathbf{P} \times \mathbf{u}) = \mu_0 \frac{\partial \mathbf{D}}{\partial t}, \qquad (4)$$

$\mathbf{u}$ being the velocity vector of the medium. The electric displacement is defined[29] as $\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P}$ and the polarization is given[30] by $\mathbf{P} = \varepsilon_0(\kappa - 1)(\mathbf{E} + \mathbf{v} \times \mathbf{B})$, ε_0 being the permittivity of free space and κ the relative permittivity also known as the dielectric constant. Since $\mathbf{v}$ and $\mathbf{u}$ are the same, the fourth Maxwell equation:

$$\nabla \times (\mathbf{B} - \mu_0 \mathbf{P} \times \mathbf{u}) = \mu_0 \frac{\partial \mathbf{D}}{\partial t}$$

$$\Updownarrow$$

$$\nabla \times \mathbf{B} = \mu_0 \left(\frac{\partial \mathbf{D}}{\partial t} + \nabla \times (\mathbf{P} \times \mathbf{u}) \right)$$

can be written as:

$$\begin{aligned}
\nabla \times \mathbf{B} &= \mu_0 \left(\varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \frac{\partial \mathbf{P}}{\partial t} + \nabla \times (\varepsilon_0(\kappa - 1)(\mathbf{E} + \mathbf{u} \times \mathbf{B}) \times \mathbf{u}) \right) \\
&= \mu_0 \left(\varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} + \varepsilon_0(\kappa - 1) \frac{\partial \mathbf{E}}{\partial t} + \varepsilon_0(\kappa - 1) \frac{\partial}{\partial t}(\mathbf{u} \times \mathbf{B}) + \nabla \times (\varepsilon_0(\kappa - 1)(\mathbf{E} \times \mathbf{u} + (\mathbf{u} \times \mathbf{B}) \times \mathbf{u})) \right) \\
&= \mu_0 \left(\varepsilon_0 \kappa \frac{\partial \mathbf{E}}{\partial t} + \varepsilon_0(\kappa - 1) \frac{\partial}{\partial t}(\mathbf{u} \times \mathbf{B}) + \nabla \times (\varepsilon_0(\kappa - 1)(\mathbf{E} \times \mathbf{u} + (\mathbf{u} \times \mathbf{B}) \times \mathbf{u})) \right) \\
&\approx \mu_0 \left(\varepsilon_0 \kappa \frac{\partial \mathbf{E}}{\partial t} + \varepsilon_0(\kappa - 1) \frac{\partial}{\partial t}(\mathbf{u} \times \mathbf{B}) + \varepsilon_0(\kappa - 1) \nabla \times (\mathbf{E} \times \mathbf{u}) \right).
\end{aligned}$$

The term $(\mathbf{u} \times \mathbf{B}) \times \mathbf{u}$ is neglected since it gives u in second order which compared to the speed of light is very small and therefore ignored. We assume the water moves with a

[28] [16] (9-20)
[29] [8] (4.10)
[30] [16] (9-19)

constant velocity which gives us $\frac{\partial \mathbf{u}}{\partial t} = 0$ and

$$\frac{\partial}{\partial t}(\mathbf{u} \times \mathbf{B}) = \frac{\partial}{\partial t}\mathbf{u} \times \mathbf{B} + \mathbf{u} \times \frac{\partial}{\partial t}\mathbf{B} = \mathbf{u} \times \frac{\partial \mathbf{B}}{\partial t}.$$

Then

$$\nabla \times \mathbf{B} = \mu_0 \left(\varepsilon_0 \kappa \frac{\partial \mathbf{E}}{\partial t} + \varepsilon_0 (\kappa - 1) \left(\mathbf{u} \times \frac{\partial \mathbf{B}}{\partial t} + \nabla \times (\mathbf{E} \times \mathbf{u}) \right) \right)$$

and by using the third Maxwell equation:

$$\begin{aligned}
\nabla \times \mathbf{B} &= \mu_0 \left(\varepsilon_0 \kappa \frac{\partial \mathbf{E}}{\partial t} + \varepsilon_0 (\kappa - 1) \left(-\mathbf{u} \times (\nabla \times \mathbf{E}) + \nabla \times (\mathbf{E} \times \mathbf{u}) \right) \right) \\
&= \mu_0 \varepsilon_0 \kappa \left(\frac{\partial \mathbf{E}}{\partial t} + (1 - \frac{1}{\kappa}) \left(-\mathbf{u} \times (\nabla \times \mathbf{E}) + \nabla \times (\mathbf{E} \times \mathbf{u}) \right) \right) \\
&= \frac{\kappa}{c^2} \left(\frac{\partial \mathbf{E}}{\partial t} + (1 - \frac{1}{\kappa}) \left(-\mathbf{u} \times (\nabla \times \mathbf{E}) + \nabla \times (\mathbf{E} \times \mathbf{u}) \right) \right) \qquad \text{because } c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}.
\end{aligned}$$ [31]

Using the vector triple product we get[32]

$$\mathbf{u} \times (\mathbf{E} \times \mathbf{u}) = \nabla(\mathbf{u} \cdot \mathbf{E}) - \mathbf{E}(\mathbf{u} \cdot \nabla).$$

Taking the curl of a cross product we get[33]

$$\nabla \times (\mathbf{E} \times \mathbf{u}) = (\mathbf{u} \cdot \nabla)\mathbf{E} - (\mathbf{E} \cdot \nabla)\mathbf{u} + \mathbf{E}(\nabla \cdot \mathbf{u}) - \mathbf{u}(\nabla \cdot \mathbf{E}).$$

The first Maxwell equation gives us $\nabla \cdot \mathbf{E} = 0$ and the constant velocity gives us $\nabla \cdot \mathbf{u} = 0$ and $(\mathbf{E} \cdot \nabla)\mathbf{u} = 0$. Then

$$\nabla \times \mathbf{B} = \frac{\kappa}{c^2} \left(\frac{\partial \mathbf{E}}{\partial t} + (1 - \frac{1}{\kappa}) \left(2(\mathbf{u} \cdot \nabla)\mathbf{E} - \nabla(\mathbf{u} \cdot \mathbf{E}) \right) \right).$$

Let us take the curl of this equation starting with the left hand side[34]:

$$\begin{aligned}
\nabla \times (\nabla \times \mathbf{B}) &= \nabla(\nabla \cdot \mathbf{B}) - \nabla^2 \mathbf{B} \\
&= -\nabla^2 \mathbf{B}, \qquad \text{because Maxwell (2) states } \nabla \cdot \mathbf{B} = 0.
\end{aligned}$$

[31] [8] (9.42)
[32] Using (2) inside the cover of [8]
[33] Using (8) inside the cover of [8]
[34] Using (11) inside the cover of [8]

Now the right hand side:

$$
\begin{aligned}
&\nabla \times \left(\frac{\kappa}{c^2} \left(\frac{\partial \mathbf{E}}{\partial t} + (1 - \frac{1}{\kappa})(2(\mathbf{u} \cdot \nabla)\mathbf{E} - \nabla(\mathbf{u} \cdot \mathbf{E})) \right) \right) \\
&= \frac{\kappa}{c^2} \left(\nabla \times \frac{\partial \mathbf{E}}{\partial t} + (1 - \frac{1}{\kappa})(2(\mathbf{u} \cdot \nabla)\nabla \times \mathbf{E} - \nabla \times \nabla(\mathbf{u} \cdot \mathbf{E})) \right).
\end{aligned}
$$

First we realize

$$
\begin{aligned}
\nabla \times \frac{\partial \mathbf{E}}{\partial t} &= \frac{\partial}{\partial t} \nabla \times \mathbf{E} \qquad \text{because space- and time derivatives can trade places.} \\
&= -\frac{\partial^2 \mathbf{B}}{\partial t^2} \qquad \text{due to Maxwell (3).}
\end{aligned}
$$

And then we see[35]

$$
\nabla \times \nabla(\mathbf{u} \cdot \mathbf{E}) = 0.
$$

Thereby giving us the equation:

$$
\nabla^2 \mathbf{B} = \frac{\kappa}{c^2} \left(\frac{\partial^2 \mathbf{B}}{\partial t^2} + (1 - \frac{1}{\kappa}) 2(\mathbf{u} \cdot \nabla) \frac{\partial \mathbf{B}}{\partial t} \right).
$$

In the case of the Fizeau experiment we look at a wave propagating in the direction $\mathbf{n}$ along a x-axis which we define as the direction of the water. This means that

$$
\mathbf{u} \cdot \nabla = \mathbf{u} \cdot \mathbf{n} \frac{\partial}{\partial x} = -\frac{\mathbf{u} \cdot \mathbf{n}}{v_0} \frac{\partial}{\partial t} \qquad \text{because } x = -v_0 t.
$$

Thereby we get the wave equation in the known form:

$$
\begin{aligned}
\nabla^2 \mathbf{B} &= \frac{\kappa}{c^2} \left(\frac{\partial^2 \mathbf{B}}{\partial t^2} - (1 - \frac{1}{\kappa}) 2 \frac{\mathbf{u} \cdot \mathbf{n}}{v_0} \frac{\partial^2 \mathbf{B}}{\partial t^2} \right) \\
&= \frac{\kappa}{c^2} \left(1 - 2(1 - \frac{1}{\kappa}) \frac{\mathbf{u} \cdot \mathbf{n}}{v_0} \right) \frac{\partial^2 \mathbf{B}}{\partial t^2}.
\end{aligned}
$$

The speed of the propagating wave is then expressed by[36]

$$
\begin{aligned}
v &= \left[\frac{\kappa}{c^2} \left(1 - 2 \left(1 - \frac{1}{\kappa} \right) \frac{\mathbf{u} \cdot \mathbf{n}}{v_0} \right) \right]^{-1/2} \\
&= \frac{c}{\sqrt{\kappa}} \left[1 - 2 \left(1 - \frac{1}{\kappa} \right) \frac{\mathbf{u} \cdot \mathbf{n}}{v_0} \right]^{-1/2} \\
&\approx \frac{c}{\sqrt{\kappa}} \left[1 + \left(1 - \frac{1}{\kappa} \right) \frac{\mathbf{u} \cdot \mathbf{n}}{v_0} \right] \qquad \text{for } |\mathbf{u}| << v_0.^{37}
\end{aligned}
$$

The dielectric constant can be expressed by[38] $\kappa = n^2$ and the speed of light in stagnant

[35] Using (10) inside the cover of [8]

[36] [8] (9.2)

[37] Using the first order Taylor expansion. Explained shortly in section 3.2.3

[38] [8] (9.70)

water is $v_0 = c/n$ which gives us

$$\begin{aligned} v &= \frac{c}{n}\left[1+\left(1-\frac{1}{n^2}\right)\frac{\mathbf{u}\cdot\mathbf{n}}{c/n}\right] \\ &= \frac{c}{n}+\left(1-\frac{1}{n^2}\right)\mathbf{u}\cdot\mathbf{n}. \end{aligned}$$

This is the same equation as equation (2) and equation (3) below. This equation derives the same way into

$$\Delta\phi = 2L\frac{1}{\lambda}\frac{u}{c}(n^2-1).$$

3.2.3 Modern Relativistic Interpretation

A corner stone in modern special theory of relativity is the Lorentz transformations. Consider the two frames S and S' with parallel axis and coinciding origo where S' is moving with speed u along the x-axis of S. The Lorentz transformations is here presented as follows:

Direct transformation	Inverse Transformation
$x' = \gamma(x-ut)$	$x = \gamma(x'+ut')$
$y' = y$	$y = y'$
$z' = z$	$z = z'$
$t' = \gamma\left(t-\frac{u}{c^2}x\right)$	$t = \gamma\left(t'+\frac{u}{c^2}x'\right)$.

To explain the ether drag experiment there is also need of a transformation of velocity (v). In deriving this transformation we simply look at the equation of motion in the two frames: $x = vt$ and $x' = v't'$. We then calculate a transformation of velocity:

$$v' = \frac{x'}{t'} = \frac{\gamma(x-ut)}{\gamma\left(t-\frac{u}{c^2}x\right)} = \frac{x-ut}{t-\frac{u}{c^2}x} = \frac{\frac{x}{t}-u}{1-\frac{u}{c^2}\frac{x}{t}} = \frac{v-u}{1-\frac{uv}{c^2}}.$$

By a synchronous calculation we get:

$$v = \frac{v'+u}{1+\frac{v'u}{c^2}}.$$

In the Fizeau experiment we define the frame S as being stationary according to the table and S' as moving along the water with a velocity of u. This way the water is at rest in frame S' and the light is moving with a speed of $v' = \frac{c}{n}$ (n being the refractive index of water), while the light moves at the speed of v^+ along the water flow and v^- against the water flow in the S-frame:

$$v^+ = \frac{v'+u}{1+\frac{uv'}{c^2}} = \frac{\frac{c}{n}+u}{1+\frac{u}{cn}} \quad , \quad v^- = \frac{\frac{c}{n}-u}{1-\frac{u}{cn}}.$$

Using the first order Taylor approximation;

$$(1+x)^m \approx 1+mx, \quad \text{for} \quad x << 1,$$

we can simplify v^+ and v^- a bit:

$$v^+ = \frac{\frac{c}{n}+u}{1+\frac{u}{cn}} = \left(\frac{c}{n}+u\right)\left(1+\frac{u}{cn}\right)^{-1} \approx \left(\frac{c}{n}+u\right)\left(1-\frac{u}{cn}\right) \quad , \quad \left(\text{because} \quad u << cn \Leftrightarrow 1 << \frac{u}{cn}\right)$$
$$= \frac{c}{n}+u\left(1-\frac{1}{n^2}\right)-\frac{u^2}{cn} \approx \frac{c}{n}+u\left(1-\frac{1}{n^2}\right).$$

By a synchronous calculation we get the corresponding expression for v^- and write generally:

$$v^{\pm} \approx \frac{c}{n} \pm u\left(1-\frac{1}{n^2}\right). \tag{3}$$

When the light moves both directions through a water pipe of length L it is possible to calculate the total difference in travel time the following way[39]:

$$\Delta t = t^- - t^+ = \frac{L}{v^-} - \frac{L}{v^+} \approx \frac{L}{\frac{c}{n}-u\left(1-\frac{1}{n^2}\right)} - \frac{L}{\frac{c}{n}+u\left(1-\frac{1}{n^2}\right)}$$
$$= \frac{L\left(\frac{c}{n}+u\left(1-\frac{1}{n^2}\right)\right)-L\left(\frac{c}{n}-u\left(1-\frac{1}{n^2}\right)\right)}{\left(\frac{c}{n}-u\left(1-\frac{1}{n^2}\right)\right)\left(\frac{c}{n}+u\left(1-\frac{1}{n^2}\right)\right)} = \frac{2Lu\left(1-\frac{1}{n^2}\right)}{\left(\frac{c}{n}\right)^2+\left(\frac{u}{n^2}\right)^2(n^2-1)^2}$$
$$\approx \frac{2Lu\left(1-\frac{1}{n^2}\right)}{\left(\frac{c}{n}\right)^2} \quad , \quad \left(\text{small change because} \quad c >> u \Rightarrow \left(\frac{c}{n}\right)^2 >> \left(\frac{u}{n^2}\right)^2(n^2-1)^2\right)$$
$$= \frac{2Lu}{c^2}(n^2-1).$$

In the Fizeau experiment the two light beams are joined together after their different paths to form an interference pattern. This pattern will shift when the water flow is varied and the shift can be calculated using the difference in travel time. The difference in travel

[39]The following calculations are time analogous to the distance calculations performed in section 3.2.3

time can be converted to a difference in travel length; $\Delta x = \Delta t \cdot c$, and the difference in travel length can then be converted to the total interference pattern shift by dividing by the wavelength of the light (λ):

$$\Delta\phi = \frac{\Delta x}{\lambda} = \frac{\Delta t \cdot c}{\lambda} \approx \frac{c}{\lambda}\frac{2Lu}{c^2}(n^2 - 1) = 2L\frac{1}{\lambda}\frac{u}{c}(n^2 - 1). \tag{4}$$

4
The Experiment

Figure 4: The data collection screen.

4.1 History of the Setup

A little over a decade ago the construction of this setup began. The ambition was to build a mobile demonstration experiment based on the original Fizeau experiment. The cornerstone of the setup is the table mounted water flow system which was originally designed and build in the beginning. The experiment never became functional and was put on hold until 2008 when an undergrad student resumed the work. His contribution included bringing a different and stronger pump and a new flowmeter to the setup. The second attempt however did not prove fruitful and the experiment was once again put on hold without ever showing the wanted result. In the spring of 2014 I got to work on the project and the following chapter will describe the extent of my work.

4.1.1 The Setup from the Basement

The generel design of the table mounted water flow system was intact when brought back from the basement and is depicted in Figure 5. The table mounted flow system mainly consists of two long transparent pipes with a window section at each end allowing light to enter. The windows are integrated in the corner of the flow system which connects the two transparent pipes in one end and serves as an entrance and an exit in the other

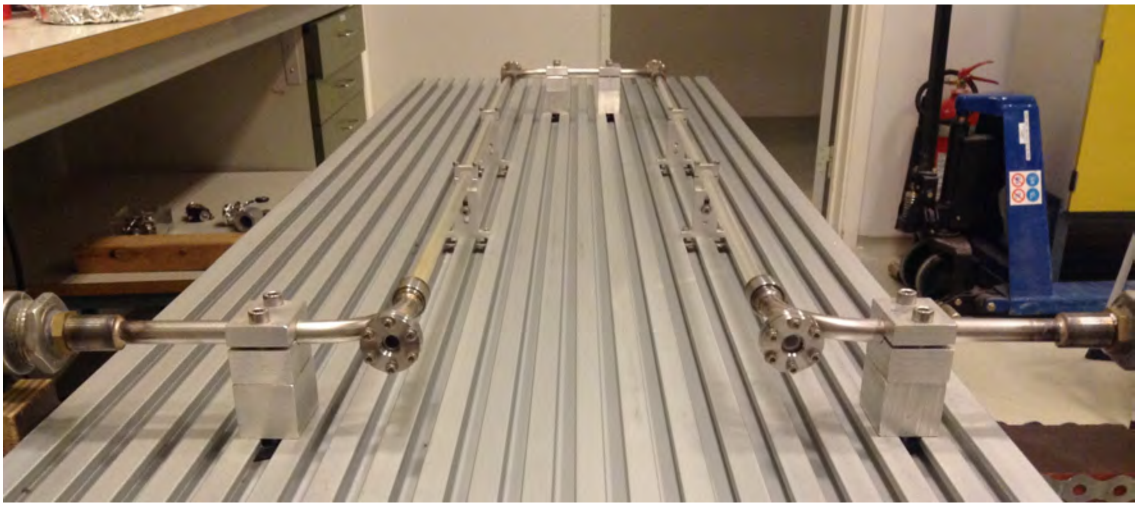


Figure 5: The original design of the table mounted water flow system.

end. The corner/window section is depicted from above in Figure 6 where the window is fixed inside the construction on the right side of the photo. Before the water enters the table mounted part of the water flow system the pipes narrow from an internal diameter of approximately 2.6cm to 0.6cm. This narrowing is shown in Figure 7, in company of a 90 degree pipe which directs the water flow from a vertical to a horizontal direction. The second part of the flow system you find in Figure 8 in which the following is depicted: the pump (on the right), the power supply (the gray box with a green on/off switch), the water reservoir (the blue box at the bottom), the pump entrance pipe (the grey pipe mounted on top of the pump with an internal diameter of about 0.6cm), the flowmeter (the black component with a digital display), a ball valve (with a red handle) and the exit tube (a robust hard rubber tube which in the picture runs back into the water reservoir). When the flow system was fully put together the black hard rubber tube was connected to the table at the entrance and the table exit tube ran back into the water reservoir.
The interferometer in the 2008-setup consisted of a 1mW HeNe laser, four mirrors and a beamsplitter.
Upon taking over on the project I was told that the interferometer, in 2008, was functional and produced a nice interference pattern until the water flow system was turned on. When the water got moving the interference pattern vanished. The pump was suspected to be the cause of the problem as it would shake and the vibrations would travel to the table and on to the mirrors. It was furthermore recommended that the setup needed a stronger

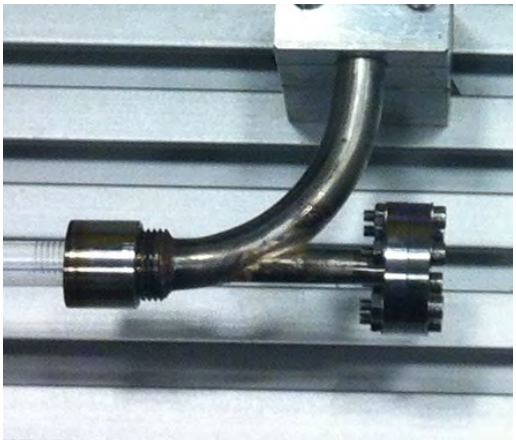


Figure 6: Window/corner of the water flow system.

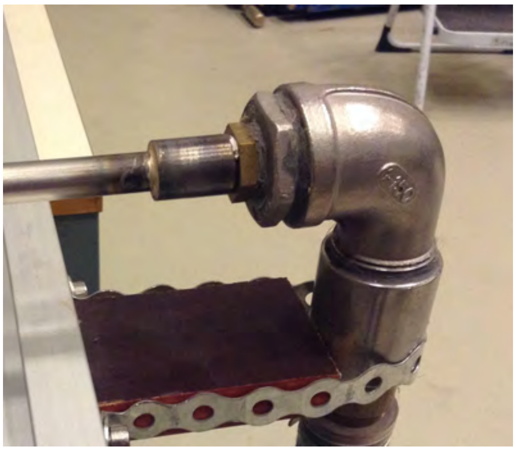


Figure 7: 90 degree pipe before narrowing into the entrance of the water flow system.

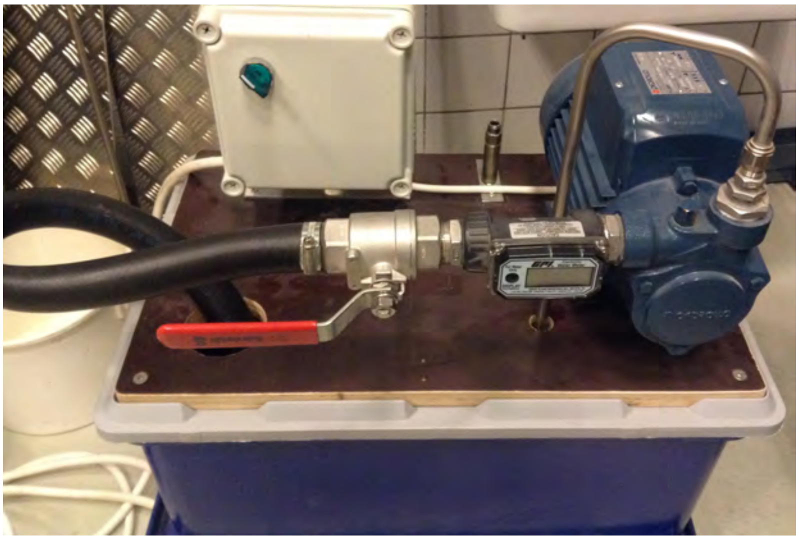


Figure 8: The second part of the water flow system.

laser.

4.1.2 Improvements to the Setup

The main problem of the 2008 setup seemed to be the shaking. After putting together the setup as it was, I observed the vibration along with some other possible improvements I could bring to the design. I too saw the shaking as a problem but another big problem was the control of the flow system. The flow were to be controlled by a ball valve which for one causes great turbulence within the water but mainly is extremely imprecise when setting a specific flow rate. I also had to deal with the shaking but first, I had to determine

Figure 9: Narrowing along side the long small rubber tube.

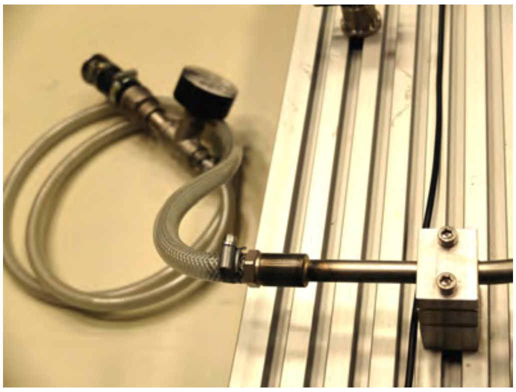


Figure 10: The entrance onto the table along side the tube and narrowing.

the cause of it. The pump was clearly a problem since it would vibrate a lot upon running. The vibrations would travel within the water and the along hard rubber tube onto the table and to the mirrors which when vibrating can not be used in an interferometer. But another cause of the shaking would seem to be the narrowing and the 90 degree bend, shown in Figure 7, upon entering the table mounted flow system. The pump is industrial grade and the power and flowrate it can generate upon running, clearly caused great shanking when the water would change direction (90 degree bend) and especially when narrowed.

To solve the shaking problem caused by both the pump and the turbulence I decided to move the narrowing closer to the pump and let the water flow from the narrowing through a thin soft rubber tube (internal diameter $\approx$ 1cm) which would curve gently onto the table, shown in Figure 9 and Figure 10. Also the exit from the table was changed to a thin rubber tube which would curve gently and run all the way down to the water reservoir. This way the turbulence and the shaking would be at maximum farther away from the table and decrease along the thin rubber tube in such a way that the vibration would be vanishingly small once the water reached the table. To reduce the shaking of the pumpe even more the small entrance pipe was replaced by a larger rubber tube. Figure 11 is a picture of the new setup close to the pump in which you see both the new entrance tube and the narrowing (on the far left).

Figure 11 furthermore shows that the power supply has been changed. I decided that the problem of controlling the flow rate should not be solved by introducing a new type of valve. Instead I changed the power supply to a frequency converter which allows the user

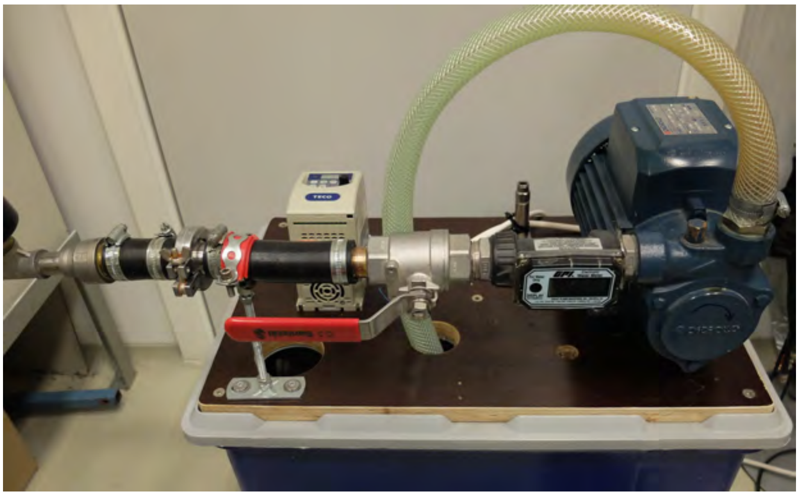


Figure 11: The new setup at the pump.

of the setup to vary the flow rate with good accuracy. The flow rate can be varied either by at set of up/down arrow buttons of by a turning knob.

Additional add-ons was an old but strong 10mW HeNe laser and a way of collecting data using a webcam which I will further elaborate on later. The intensity of the laser is important for two reasons. First, a clear and strong interference pattern is always preferable. Second, when using a closed flow circuit various sediments easily get into the system and will pile up hence making the water less transparent.

4.2 Final Setup

The improvements that was made proved sufficient to bring down the vibrations hence making the experiment possible. The strategy of forcing the vibrations to stay close to the pump made it possible to keep the mobility of the setup as it can still be parted into two, the table and the water reservoir/pump, thereby letting it remain a transportable demonstration experiment. The experiment mainly consist of two parts, the interferometer and the water flow system, which is elaborated separately below.

4.2.1 The Water Flow System

The main requirement to get the experiment to work is to get a proper steady flow in which we can let light travel through. The flow is supplied by the pump which through some neat piping lets the water flow without too much vibration. The flow rate is controlled by a frequency converter which instead of letting the pump run on 50Hz, which is customary in Danish outlets, varies the frequency. The display on the frequency converter shows which frequency it generates and a calibration is needed to know the velocity of the water in the pipes. A flow meter shows how many liters of water that has gone through the system since in was mounted. The calibration was preformed by letting the water flow at a given frequency, then timing how many liters of water went through the system. Since the laser only travels within water in the transparent pipes we have an internal diameter of d= 0.6cm, hence we can calculate the velocity of the water. To calculate the velocity (u) through these pipes we define the flow rate as $Q = \frac{\Delta V}{\Delta t}$, V being the volume of water and t the time, and calculate how much water passes through a cross section ($A = \pi r^2$, $r = d/2$) of the tube per time:

$$u = \frac{Q}{A}.$$

Table 1: Frequency to velocity calibration data. The pump ran for 170 seconds

Frequency [Hz]	Volume [liters]	u [m/s]
2.7 ± 0.1	0	0
10.0 ± 0.1	10.0 ± 0.5	2.1 ± 0.1
15.0 ± 0.1	18.0 ± 0.5	3.7 ± 0.1
20.0 ± 0.1	26.0 ± 0.5	5.3 ± 0.1
25.0 ± 0.1	32.0 ± 0.5	6.7 ± 0.1
30.0 ± 0.1	39.0 ± 0.5	8.1 ± 0.1
35.0 ± 0.1	46.0 ± 0.5	9.5 ± 0.1
40.0 ± 0.1	52.0 ± 0.5	10.7 ± 0.1
45.0 ± 0.1	53.0 ± 0.5	11.1 ± 0.1

Table 1 contains the calibration data while a plot of the data along with two fitted functions can be found in Figure 12. The deviations of the frequency and the volume were estimated on how precise the display of the frequency converter and the flow meter was. The deviation on the velocity of the water was found by performing ten measurements at a constant velocity and calculating the standard deviation. The linear fit does not include the data point at 45Hz because something peculiar happens here. The data seems to ”bend” after 40Hz, which is probably caused by two of the following three possibilities. First, the flowmeter can be imprecise at our high velocities and therefore not show the

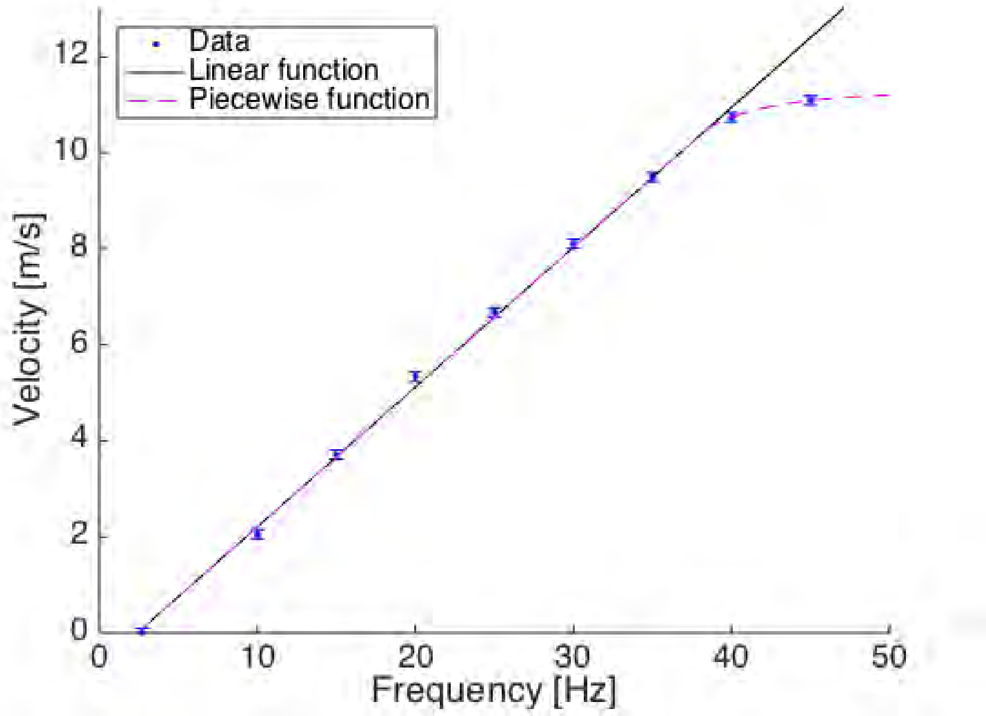


Figure 12: Plot of the frequency calibration.

correct consumption. This however is not the case since our top flow rate is below 20 lpm and the flowmeter is build for a maximum flow rate of 100 lpm[40]. Second, the pump was originally powered by a 400V outlet but the frequency converter is only hooked up to a standard 220V outlet. The frequency in the danish outlets is as mentioned 50Hz, but the frequency converter seems to reach a maximum at 46Hz. This implies that the frequency converter reaches a overload above 45Hz. One could go back to the larger power outlet but this would compromise the mobility since most auditoriums does not have a 400V outlet. Third, we have reached a point where the pump cannot preform a larger flow rate due to pressure inside the pipes. This possibility is of course linked to the second one since the pump need more power to produce a larger flow rate. The pump should be able to produce a higher flow rate according to the data sheet[41] but because we narrow the pipe a lot, the pressure rises faster and sets the maximum for the performance of the pump. The point being that I accepted the maximum flow rate and constructed a piecewise function

[40] [22]
[41] [23]

Figure 13: Overview of the setup.

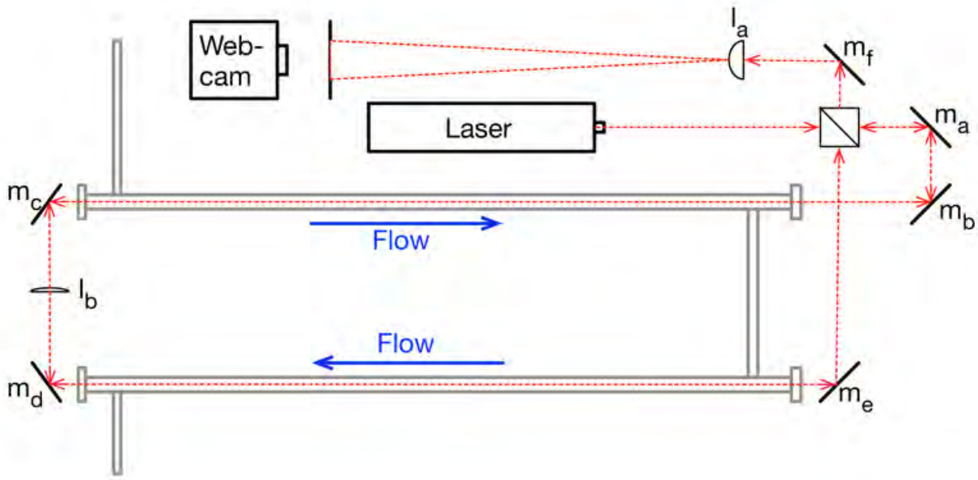


Figure 14: Diagram of the setup.

to account for the ”bend” in our plot:

$$u(f) = \begin{cases} 0.2912 \cdot f - 0.7026 & \text{for } f \leq 38.5Hz \\ -1.614 \cdot 10^{14} \cdot f^{-9.039} + 11.27 & \text{for } f > 38.5Hz \end{cases}$$

$u(f)$ being the velocity of the water in the transparent tubes with an internal diameter of 0.6cm according to the frequency f.

4.2.2 Interferometer

An effective way of testing the characteristics of light waves is to use the properties of superposition and create an interferometer. The interferometer is an extremely powerful optical tool that lets you test very small variations within the light, without elaborate and

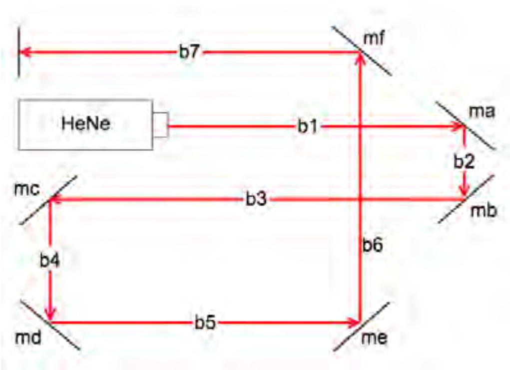


Figure 15: Diagram of the path of the beam which travels straight through the beamsplitter.

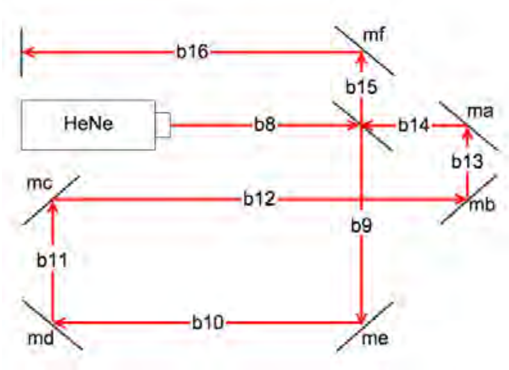


Figure 16: Diagram of the beam path which is directed in a 90 degree angle by the beamsplitter.

complex equipment. In Figure 13 the setup is depicted and a diagram of the setup can be found in Figure 14. The interferometer works by letting a laser beam pass through a beam splitter which lets one beam straight through and reflects the other in a 90 degree angle. The first beam hits mirror m_a and m_b before entering the water, it travels through the pipe and exits the water before being redirected by mirror m_c and m_d to enter the water again through the other pipe. The beam then exits the water and hits mirror m_e, goes through the beam splitter, is redirected by mirror m_f and is projected on to a screen through a lens, l_a. The second beam is redirected by the beamsplitter and first hits mirror m_e and travels the other way through the system also to be projected on to the screen. The laser beam expands a bit the farther it gets from the HeNe laser which is why lens l_b is put approximately half way through the path of the beams. Lens l_b has a focal length of about 70cm which makes sure, the beams stay a decent width until they are projected on to the screen. The focal length of lens l_a is relatively short as the goal is to widen the widths of the beams to a size of a centimeter of two.

This specific type of interferometer is called a sagnac interferometer which is a common path interferometer and are known for being especially stable thereby making it ideal as the foundation of our mobile setup. It becomes stable through the geometry of the placement of the mirrors. In Figure 15 you see the path of the first beam through the interferometer, to demonstrate the stability lets say that one where to pull mirror m_d directly west on the diagram. This would result in a change in distance the beams

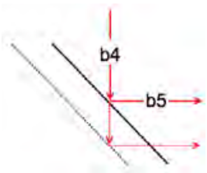


Figure 17: Diagram of the beam b4 hitting mirror m$_d$.

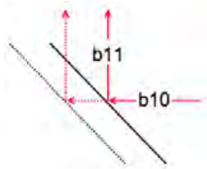


Figure 18: Diagram of the beam b10 hitting mirror m$_d$.

would travel between the mirrors. If we assume that pulling the mirror do not influence the 90 degree angles of the redirection of the beams and the mirror gets pulled only in the x,y plane of the setup we can predict the change in distance between the mirrors. When the m$_d$ mirror gets pulled west the arrow end of b4 gets longer, this we notate as b4$_{\uparrow,1/2}$, since b5, at mirror m$_d$, behaves as shown in Figure 17 it gets shorter only in the arrow end, b5$_{\downarrow,1/2}$, if the path of the beam is followed ones sees that b6 gets longer in both ends, b6$_{\uparrow}$, and b7$_{\downarrow,1/2}$. This gives us a surplus of the arbitrary unit: b4$_{\uparrow,1/2}$+b5$_{\downarrow,1/2}$+b6$_{\uparrow}$+b7$_{\downarrow,1/2}$ =bI$_{\uparrow,1/2}$ (keep in mind that beams b1-b3 are not affected). If we look at the same situation, of mirror m$_d$ getting pulled west, then the second beam path, depicted in Figure 16, must undergo the following changes: b10$_{\uparrow,1/2}$ (Figure 18), b11$_{\downarrow,1/2}$, b13$_{\uparrow}$ and b16$_{\downarrow,1/2}$. This time b8 and b9 are not affected and the mirrors at each end of b12, b14 and b15 are parallel which results in zero change in length. The total change in length this time around is: b10$_{\uparrow,1/2}$+b11$_{\downarrow,1/2}$+b13$_{\uparrow}$+b16$_{\downarrow,1/2}$ =bII$_{\uparrow,1/2}$. Since the mirror keeps the 90 degree reflection, the paths that shorten impacting the mirror must shorten by the exact amount that out coming paths lengthen. This gives us that the two paths are lengthened by the same amount, bI$_{\uparrow,1/2}$ =bII$_{\uparrow,1/2}$, hence no change will occur in the interference pattern. A second example could be pulling mirror m$_c$ north which again would result in the same change in distance travelled by the two beams: b3$_{\uparrow,1/2}$+b4$_{\downarrow,1/2}$+b5$_{\uparrow}$+b6$_{\downarrow}$+b7$_{\uparrow,1/2}$ =bI$_{\uparrow,1/2}$ =bII$_{\uparrow,1/2}$ =b11$_{\uparrow,1/2}$+b12$_{\uparrow,1/2}$+b13$_{\downarrow}$+b16$_{\uparrow,1/2}$. I have tested this in the lab and the interference pattern is extremely stationary when touching the mirrors compared to at setup of the Michelson Morley interferometer. A more rigorous mathematical argument could be made to support this theory but as I ran out of time the above, some what shallow argument, must suffice.

A simple sagnac interferometer consists of a laser, three mirrors and a beamsplitter. I

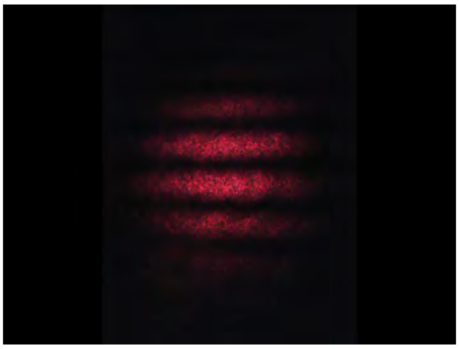


Figure 19: A picture taken behind the paper screen by the web camera thus making up the raw data.

added some mirrors for conveniency and also to be able to do a parallel shift of the beam which goes straight through the beamsplitter. If mirrors m_a and m_b was not added the laser would have to be perfectly aligned at a constant hight, with mirrors m_a and m_b added we can align the hight by using the mechanisms on the mirror mounts.

4.2.3 Data Acquisition

In Figure 4 the data collection screen is depicted. The screen in reality is a peace of normal white printable paper which have the convenient property of being partly transparent hence showing the interference pattern, projected on to it, on the back side as well. I have placed an extremely affordable web camera behind the screen which takes pictures of the interference pattern. An example of the raw picture is found in Figure 19. Using a web camera was inspired by Lahaye[42] even though their method was a little different. Lahaye stripped the web camera of it's lens and projected the interference pattern directly on to the detector chip and adjusted the mirrors to give them a view of approximately ten interference bands, but not the beginning or the end of the pattern. My method turned out, in hindsight, to be a great choice, but more on that later.

4.3 Data Processing

The basis of the data processing is build around the matlab function improfile. improfile follows a defined line and plots the intensity of the light along this line. To make sure the program did not give imprecise results by encountering impurities on the photo I made

[42][11]

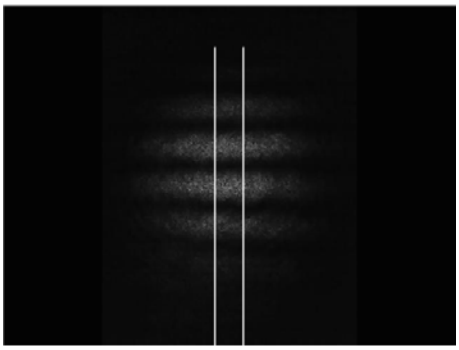


Figure 20: A black and white version of Figure 19 with the improfile interval between the two white lines.

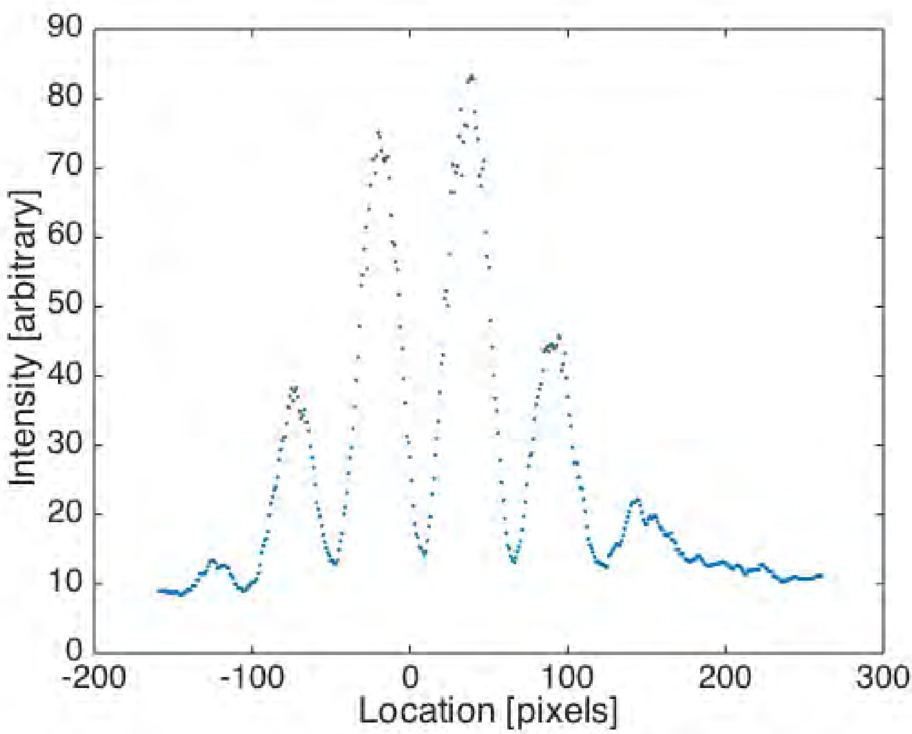


Figure 21: Intensity plot of the data collected in Figure 20.

it draw 40 lines parallel to each other at a distance of one pixel from one another. In Figure 20 you see the interval which the 40 line was drawn within and in Figure 21 the intensity plot of this area. In order to analyze the data according to the theory, which gives equation (4):

$$\Delta\phi = 2L\frac{1}{\lambda}\frac{u}{c}(n^2 - 1),$$

we have to know how much each interference band shifts upon adjusting the water velocity. When taking a look at the data in Figure 21 one quickly recognises the wave structure. But it is evident that we can not fit a wave function directly to this data. We must construct an envelope function to meet our requirements.

4.3.1 Envelope Function

As the data seems to be aligned at the bottom of the wave, we start by including the following wave function

$$f_1(x) = \sin^2(k \cdot x + \delta).$$

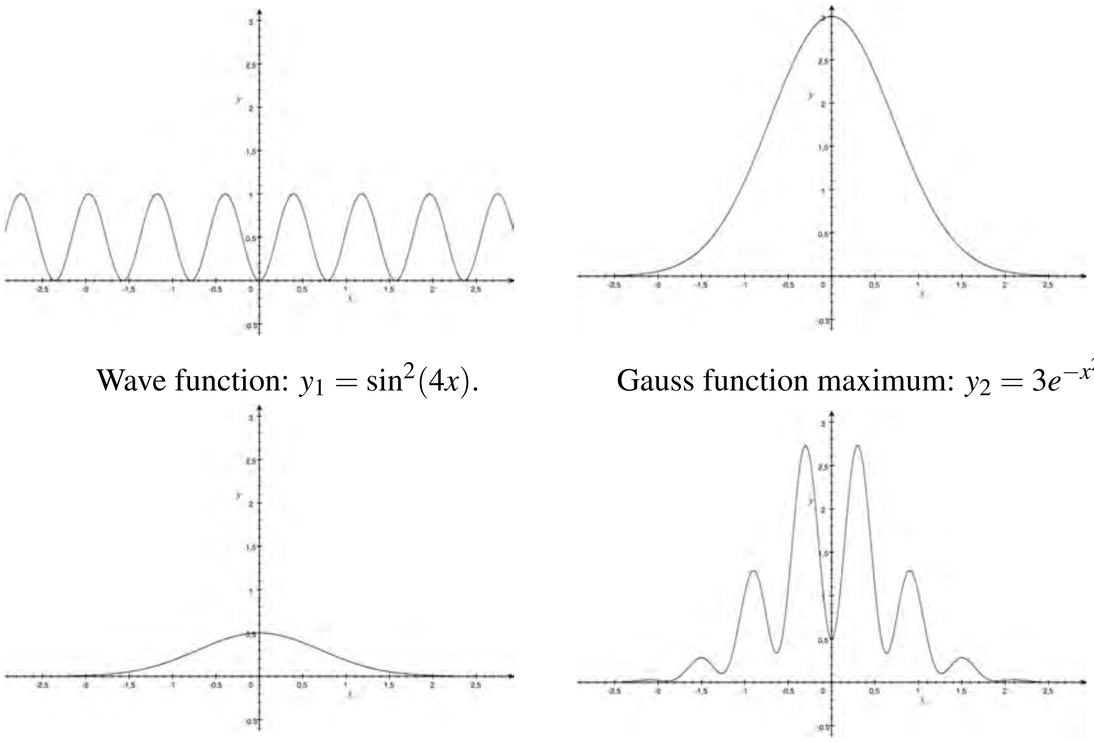
The wavenumber k is related to the wavelength by $\lambda = \frac{2\pi}{k}$ and the phase constant δ is related to the displacement of the wave by $\phi = \frac{\delta}{k}$. To make a proper envelope function for curve fitting we must limit the wave function $f_1(x)$ both at the top and at the bottom by a set of gaussian functions. We let the top of the function be limited by:

$$f_2(x) = I_1 \cdot exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

and the bottom be limited by:

$$f_3(x) = I_2 \cdot exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right).$$

Since the placement and width of the two gauss functions should be the same we do not define separate μ and σ. I_1 and I_2 are the hight of the two gauss peaks, respectively. In Figure 22 you see some examples of the above mentioned functions and what happens when we combine them into an envelope function. In the general case we merge functions



Wave function: $y_1 = \sin^2(4x)$.

Gauss function maximum: $y_2 = 3e^{-x^2}$

Gauss function minimum: $y_3 = \frac{1}{2}e^{-x^2}$

Envolope function: $y = y_1(y_2 - y_3) + y_3$

Figure 22: Examples of the individual functions that make up the desired shape of our envelope function.

$f_1(x)$, $f_2(x)$ and $f_3(x)$ to our general intensity envelope function:

$$\begin{aligned} I(x) &= f_1(x) \cdot [f_2(x) - f_3(x)] + f_3(x) + I_0 \\ &= \sin^2(k \cdot x + \delta) \cdot \left[I_1 \cdot exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) - I_2 \cdot exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)\right] + I_2 \cdot exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) + I_0. \end{aligned}$$

I_0 is a constant which expresses the background intensity of light in the photos. Hereby we have the following fitting parameters in our function $I(x)$: k, δ, I_0, I_1, I_2, μ and σ.

4.3.2 Curve Fitting

Figure 23 contains a curve fit using the new envelope function on the intensity plot of Figure 21. The envelope function seems to be working quite nice and will be used generally from this point.

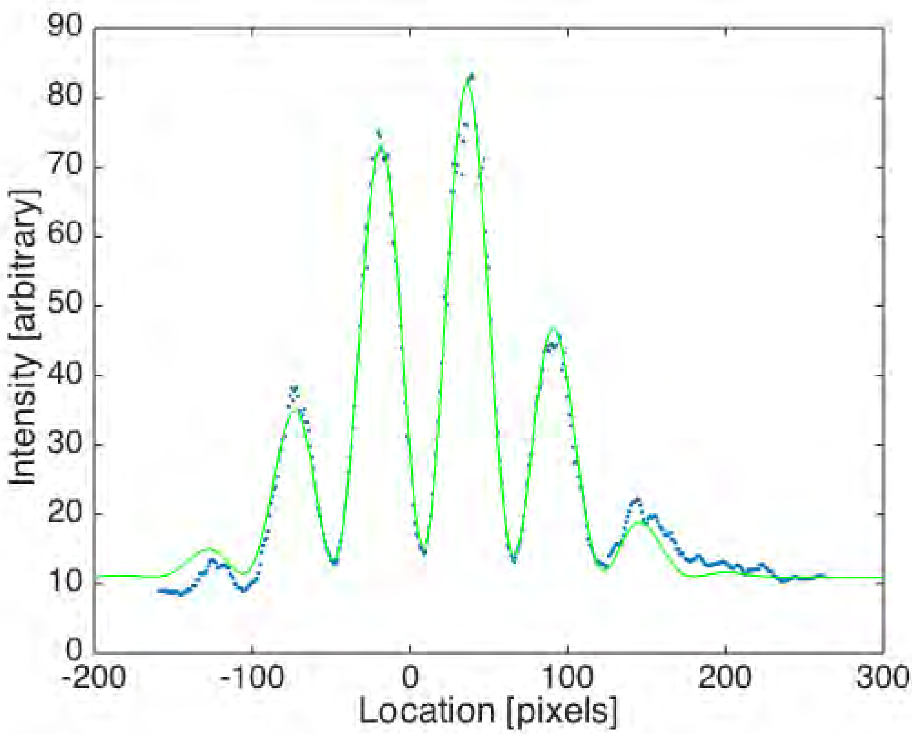


Figure 23: Intensity plot of the data collected in Figure 20 with a curve fit to the envelope function.

4.3.3 The Data

We now know how to analyze the photos taken during the execution of the experiment. The experiment was performed by setting the pump to a specific speed, hence a specific water velocity u and taking a series of 10-15 photos of the interference pattern. As the frequency converter obviously only show the frequency, put through to the pump, the water velocities was chosen from a convenient frequency setting, which can be found in Table 2. At each velocity, 10 pictures were analyzed, each picture resulting in a set of fitting parameters. The relevant values was selected and the mean value and the standard deviation of the mean value was calculated.

In the ideal case we would only need one of the fitting parameters δ to test our experiment against the theories:

$$\Delta\phi_{exp}(u) = \frac{\phi(u) - \phi_0}{\lambda} = \frac{\frac{\delta(u)\lambda}{2\pi} - \frac{\delta_0\lambda}{2\pi}}{\lambda} = \frac{\delta(u) - \delta_0}{2\pi}$$

δ_0 being the placement of the interference band at water velocity $u = 0$m/s and $\delta(u)$ being the placement when $u \neq 0$. Two things end up messing with the above equation for

Table 2: Complete set of necessary data pulled from an experiment.

Frequency [Hz]	u [m/s]	λ [pixels]	δ	ϕ [pixels]	μ [pixels]
5.0 ± 0.1	0.8 ± 0.1	116.98 ± 0.08	3.614 ± 0.010	67.28 ± 0.19	-6.0 ± 0.4
10.0 ± 0.1	2.2 ± 0.1	116.44 ± 0.21	3.671 ± 0.026	68.03 ± 0.50	-11.2 ± 0.6
15.0 ± 0.1	3.7 ± 0.1	116.08 ± 0.07	3.505 ± 0.007	64.75 ± 0.14	-7.3 ± 0.3
20.0 ± 0.1	5.1 ± 0.1	114.84 ± 0.11	3.286 ± 0.021	60.07 ± 0.38	0.2 ± 0.6
25.0 ± 0.1	6.6 ± 0.1	113.73 ± 0.09	2.984 ± 0.025	54.00 ± 0.46	8.3 ± 0.3
30.0 ± 0.1	8.0 ± 0.1	112.38 ± 0.12	2.695 ± 0.015	48.21 ± 0.28	15.3 ± 0.6
35.0 ± 0.1	9.5 ± 0.1	111.16 ± 0.08	2.410 ± 0.011	42.64 ± 0.20	26.1 ± 0.6
40.0 ± 0.1	10.7 ± 0.1	110.35 ± 0.12	2.106 ± 0.010	36.98 ± 0.17	37.6 ± 0.5
45.0 ± 0.1	11.1 ± 0.1	110.85 ± 0.13	2.010 ± 0.021	35.44 ± 0.38	40.8 ± 0.7

Figure 24: QR code which links to a video of the unstabile interference pattern at $u = 0$. Alternative to QR code, link: `goo.gl/8kuJ7k`.

Figure 25: QR code which links to a video of photos and plots during a fringe shift. Alternative to QR code, link: `goo.gl/6Dn7Ht`.

$\Delta\phi_{exp}(u)$. First, there is a huge problem with the stability of the interference pattern upon reaching $u = 0$m/s. I have taped a video showing the problem. You can find the video by scanning the QR Code[43] in Figure 24 or via the short link supplied in the caption of Figure 24. It is obvious that something odd happens upon reaching zero water velocity. I have not been able to pin point the problem of the blurring and have therefore found a different solution to the problem. Instead of using $\delta(u = 0\text{m/s})$ as a reference I use $\delta(u = 6.6\text{m/s}) := \delta_r$.

$$\Delta\phi_{exp}(u) = \frac{\delta(u) - \delta_r}{2\pi} + C.$$

As equation (4) solely is an expression of the slope it is necessary to add a constant to the expression above in order to plot the data along side of the theory, we choose the constant $C_r := \Delta\phi_{Theory}(u = 6.6\text{m/s})$. As you can see in Table 2 the measured δ is decreasing. This implies the we in fact are sending the water around the system in the negative direction

[43]Numerous apps, for scanning QR code, are developed, here are a few: for iPad - ”QR Reader for iPad”, iPhone - ”QR Reader for iPhone”, Android - ”QR Code Reader”

hence the proper notation for the velocities should have a minus sign in front of them. I however chose to multiply the experimental data by -1 thereby giving me a positive water velocity and:

$$\Delta\phi_{exp}(u) = \frac{-(\delta(u)-\delta_r)}{2\pi} + Cr = \frac{\delta_r - \delta(u)}{2\pi} + Cr$$

This I do only for aesthetic reasons as the experiment would have the same result if I stayed with the negative water velocity. Now we plot the data according to the theory of relativity and the classical theory, Figure 26. The plot shows a set of experimental data which lies right on top of the expected theory, but this, of course, is to be expected since the constant C_r is designed that way. What we are really interested in is the slope of the data but before we find that there is something peculiar about the data we must address. If one check out the video in Figure 25, it is obvious that it is not only the interference band that move but the entire dot. This is a problem that must be addressed since the value of δ contains both the fringe shift and the displacement of the dot. But is it possible to determine which part of δ is which? The envelope already contains the answer since the two gauss peaks tell the placement of the entire dot μ. I have calculated the dot displacement in the unit "fringe shift" in order to plot this data along side of $\Delta\phi_{exp}(u)$ in Figure 26:

$$\Delta\mu_{exp}(u) = \frac{\mu(u)-\mu_r}{\bar{\lambda}} + Cr,$$

$\bar{\lambda}$ being the mean value of the measured wavelengths (found in Table 2) and $\mu_r := \mu(u = 6.6\text{m/s})$. This means that in reality we cannot compare $\Delta\phi_{exp}$ and $\Delta\phi_{Theory}$ without taking $\Delta\mu_{exp}$ into account. This happens by subtracting $\Delta\mu_{exp}$ and $\Delta\phi_{exp}$:

$$\Delta\phi_{result}(u) = \Delta\mu_{exp}(u) - \Delta\phi_{exp}(u) = \frac{\mu(u)-\mu_r}{\bar{\lambda}} - \frac{\delta_r - \delta(u)}{2\pi},$$

hence the slope of the experimental data will be found by doing a linear fit on $\Delta\phi_{result}(u)$, which gives:

$$y(u) = a_{result} \cdot u + K = 0.0172 \cdot u - 0.0923.$$

Thus $K = -0.09 \pm 0.03$ and the experimental slope $a_{result} = 0.017 \pm 0.004$. Using K to relocate the data back along side the theories we plot: $\Delta\phi_{result}(u) - K$ and $y(u) - K =$

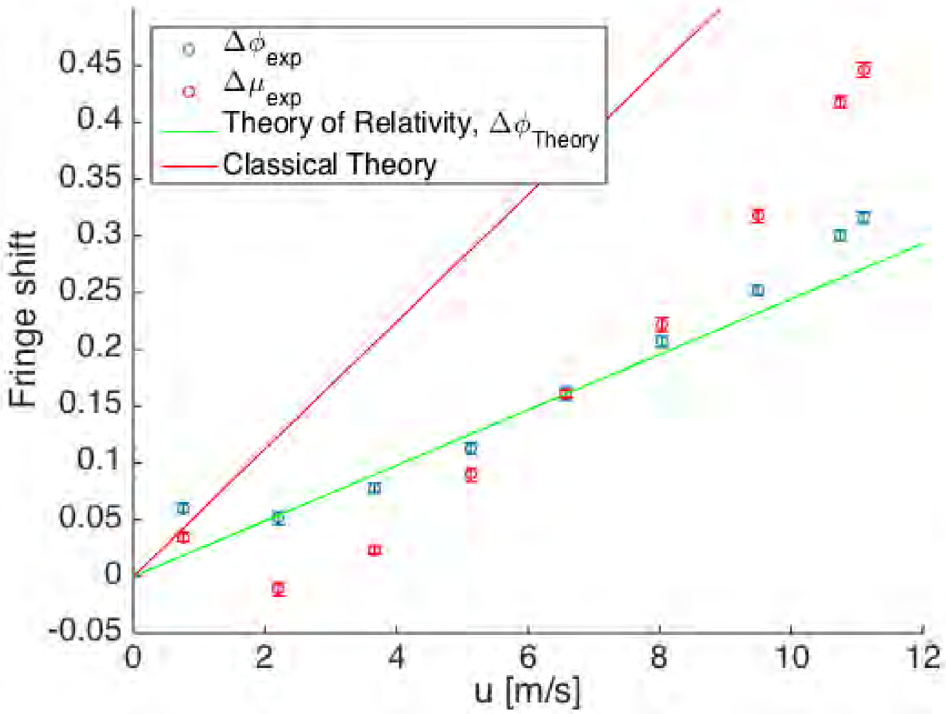


Figure 26: Experimental data vs. Theory.

$a_{result} \cdot u$, in Figure 27. According to the theory the data has to be linear which is why I made a linear fit, but in reality the data seems to curve as if the shift somehow accelerates. Observing Figure 26 ones sees that the curvature stems from the $\Delta\mu_{expo}$ data. But why does the dot seem to accelerate? This question puzzled me and to be sure that the data in fact behaved this way I preformed the experiment two times extra, the result can be found in Figure 28. It seems that something is not behaving as it should and I have concluded that the setup is not quite done yet. I suspect that the windows, that allow the laser beams to enter the water, which are connected to the corners of the table mounted flow system, are to blame for the strange behavior of the data. When applying pressure to the corners and the mirrors the interference pattern moves. As the water flows at quite large velocities it must exert some force when changing direction in the 90 degree corners. If the corners are not mounted properly they will move and the mirrors along with them, thereby moving the interference pattern which we are not interested in. To test this hypothesis I constructed a temporary and very crude mounting system (pictures can be found in Appendix A Figure 41 and Figure 42) and performed the experiment once

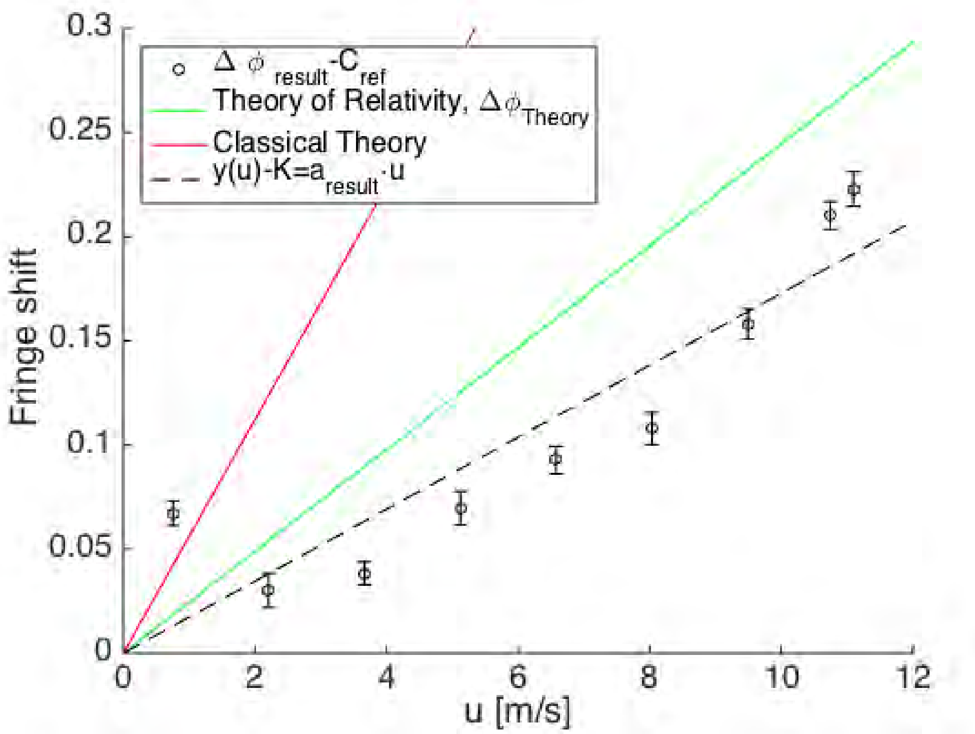


Figure 27: The final experimental result along side of the theories.

again. The result can be found in Figure 29 where it seems to behave more linear, except for a single data point. As this was only at test to see which further improvements should be made to the setup I will not try to conclude too much from the last experimental result. For good measure I present the slopes of the experiments in Table 3.

Table 3: The experimental results.

	Experimental slope	Relativistic slope	Classical slope
The three combined sets	0.019 ± 0.002	0.025	0.056
Mounted	0.029 ± 0.004	0.025	0.056

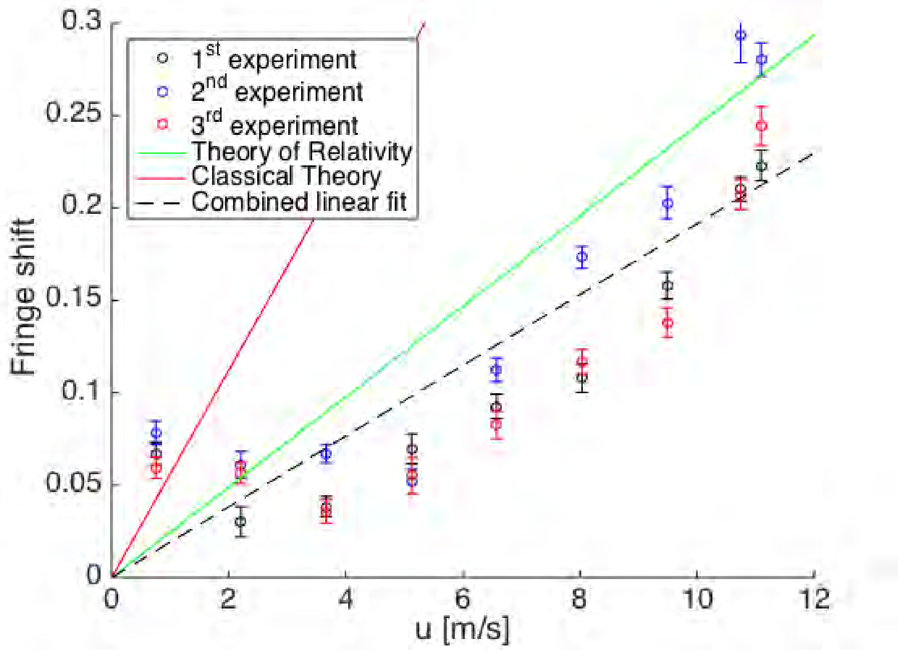


Figure 28: Three sets of data along side of the theories.

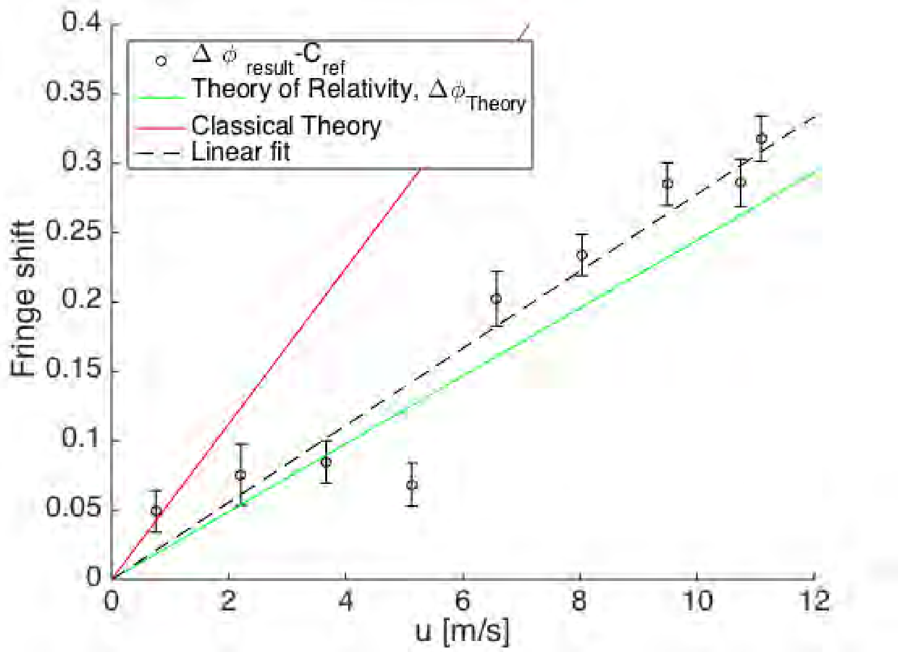


Figure 29: Data from an execution of the experiment with mounted corners.

4.3.4 DEVIATIONS

When the setup was running the interference pattern tended to fluctuate a little. This fluctuation does not show on the single photos as they are slow enough not to let the pictures blur out. This difference in the photos at a single velocity, due to the fluctuation, contribute to the uncertainties and does so larger than the uncertainties found through the curve fitting session. This is the reason why 10 photos was analyzed at each velocity. The mean value and the standard deviation of the mean value was then calculated for each of the relevant fitting parameters. For example, the mean value, the standard deviation and the standard deviation of the mean value for δ:

$$\delta = \frac{1}{n}\sum_{i=1}^{n}\delta_i$$
$$\sigma_{\delta_i} = \left(\frac{1}{n-1}\sum_{i=1}^{n}(\delta_i-\delta)^2\right)^{1/2}$$
$$\sigma_{\delta} = \frac{\sigma_{\delta_i}}{\sqrt{n}},$$

n being the number of observations in this case $n = 10$. When calculating the uncertainties for $\Delta\phi_{exp}(u)$ and $\Delta\mu_{exp}(u)$, the formula for error propagation was used to find the standard deviation:

$$\sigma_f = \sqrt{\left(\sum_{i=1}^{m}\frac{\partial f}{\partial x_i}\sigma_{x_i}\right)^2}$$

for a function f of variables $x_1,\ldots,x_m$. Since the constant C_r only was used for visible representation the uncertainty of that is not included in the calculations of $\sigma_{\Delta\phi_{exp}(u)}$ and $\sigma_{\Delta\mu_{exp}(u)}$:

$$\sigma_{\Delta\phi_{exp}} = \sqrt{\left(\frac{\sigma_{\delta_r}}{2\pi}\right)^2+\left(\frac{-\sigma_{\delta}}{2\pi}\right)^2}$$
$$\sigma_{\Delta\mu_{exp}} = \sqrt{\left(\frac{\sigma_{\mu_r}}{\bar{\lambda}}\right)^2+\left(\frac{-\sigma_{\mu}}{\bar{\lambda}}\right)^2+\left(\frac{-(\mu_r-\mu)}{\bar{\lambda}^2}\cdot\sigma_{\bar{\lambda}}\right)^2}.$$

When calculating $\Delta\phi_{result}$ I also used the error propagation:

$$\sigma_{\Delta\phi_{result}} = \sqrt{\sigma^2_{\Delta\phi_{exp}}+\sigma^2_{\Delta\mu_{exp}}}.$$

In the above I have neglected correlations because most of these calculations are not necessary once the setup is entirely functional, but strictly speaking the uncertainties in reality should be a bit bigger than they are in the plots, in Figure 27-29.

The deviations in Figure 26 seem to be quite small compared to how they are spread out but as these data is influenced by a large systematic error we cannot say if the statistical error of the data is too big or too small at this point. The systematic error I mention is in fact the $\Delta\mu_{exp}(u)$ data, I name them systematic since they systematically are to blame for the curve in the final result $\Delta\phi_{result}$ furthermore I also suspect they have something to do with the small curve of the original data $\Delta\phi_{exp}(u)$. This suspicion stems from the fact that the mounted data, does not seem to curve, see Figure 29.

4.4 Sources of Error and Other Problems

The Blur

As preciously mentioned, when the water reaches low velocities and comes to a halt the interference band and the entire laser beam dot blurs and becomes unreadable. This has been a problem from the point where the interferometer was up and running for the first time. I have tried different things to solve the problem as I suspected difference perpetrators throughout the process. I narrowed the cause of the problem to be something within the water. When the setup had been resting over night and the laser was turned on a beautiful interference pattern was to find. But after turning the water flow on and off quickly, the pattern would blur out and disappear, only to reemerge after a couple of hours. This indicates that there was some sort of sediment in the water that upon rest would fall to the bottom or sides of the pipes and once the flow was turned on it would whirl up into the water again. It also came to show that if the setup ran for more than half an hour the interference pattern became more unstable.

I first suspected the high content of lime in the water, that come from Danish faucets, were to blame. After changing the water from tap water to demineralised water and no change occurred, I was forced to reject the lime hypothesis. Second, the water seemed to contain rust and in fact there was a screw in the tank that was rusting but after concealing the screw and changing the water the blur was still to be found and rust could not be the cause of the blur. I abandoned the problem and introduced a new reference point instead of zero water velocity. Since the new reference point does not influence the slope of the data this solution is very satisfactory.

THE DOT

When varying the water velocity it is not only the interference band that moves, but also the entire dot. I am convinced that the cause of this problem is the force exerted on the corners, on which the windows are mounted, when the water changes direction. The obvious solution to this problem would be to fasten the windows to the table, which however will not be done this time around due to lack of time.

Upon discovering the movement of the dot I could not help but consider myself a tad fortunate that i did not choose to perform the data acquisition as they do in Lahaye[44]. Lahaye choose to focus the interference pattern directly on to a detector chip hence no need for a complicated envelope function, but in fact that makes it possible to neglect a potential displacement of the dot. The data acquisition of Lahaye, is depicted in Appendix A, Figure 43. Of course the potential problem would eventually have been solved but I fortunately saved some time.

THE FLOW

Throughout the calculations the assumption has been that the water moves with a mean velocity, hence the same velocity in every radial location of the pipe. Due to friction at the inner walls of the pipe this is of course a wrong assumption. If the interferometer have been aligned properly the beams should be located in the center of the pipe where the water moves faster than the mean velocity. This leaves all the above calculations with a too small expression for the velocity of the water, hence a steeper slope that it in reality should be.

4.5 TURBULENT FLOW

Due to friction at the pipe walls the velocity of the water tend to increase towards the middle of the pipe. The question of how much faster the water moves at the center com-

[44] [11] pp. 5.

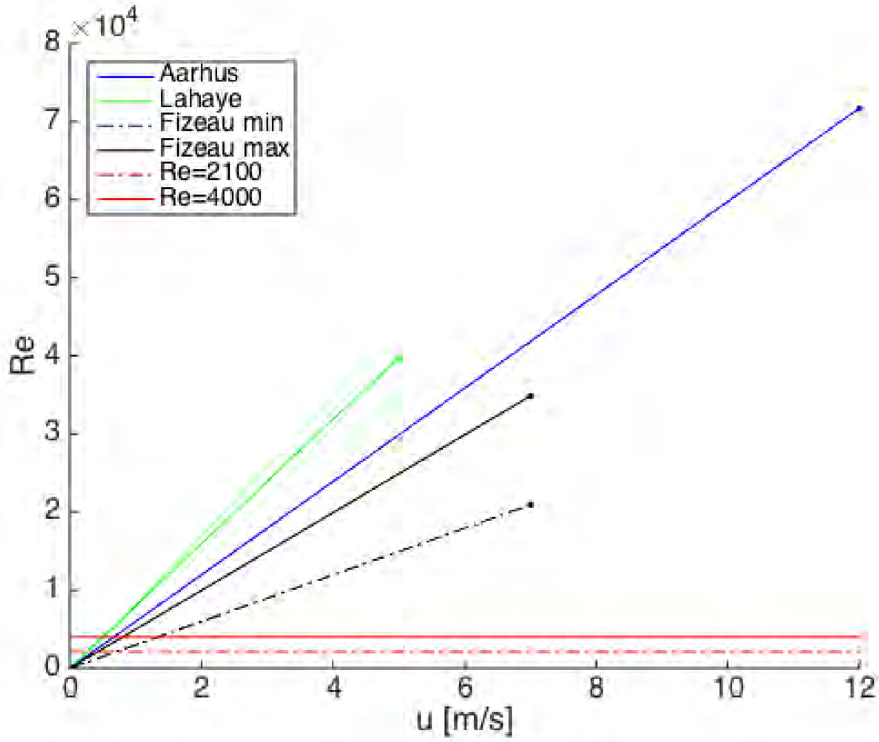


Figure 30: Reynolds number as a function of velocity in the cases of: Fizeau, Lahaye and Aarhus.

pared to the mean velocity is unfortunately a complicated question. Firstly one have to determine wether the water moves in a laminar or a turbulent manner. To determine this we look to Reynolds number which, in a pipe, is defined[45] by:

$$Re = \frac{\rho \cdot u \cdot d}{\nu}.$$

Where ρ is the density of the fluid, u the speed and ν the viscosity, while d is the inner diameter of the tube. When Reynolds number is lover than $Re < 2100$ in a tube, the fluid moves in a laminar fashion. When it exceeds $Re > 4000$ the flow is defiantly turbulent. I have calculated Reynolds number as a function of velocity u for this setup ($d = 0.6$cm) and also the setup of Fizeau ($d \in (0.3\text{cm}, 0.5\text{cm})$) and Lahaye ($d = 0.8$cm) and plotted it in Figure 30. In Figure 30 it is clear that all of the experiments mainly have to deal with turbulent flow in the pipes. The observations regarding laminar flow for $Re < 2100$ was made for long pipes and all of the above experiments have corners and Fizeau even have to deal with his pipes not being the same inner diameter all the way through. This

[45] [10] pp. 145.

means that to a good approximation the flow is turbulent within the boundaries of the experiments. The problem now is that Fluid Mechanics is a tricky business and unlike the case of laminar flow there is no analytic formula for the turbulent velocity profile within a pipe. However it is commonly believed that a turbulent velocity profile looks somewhat like the one in Figure 31. Note that the analytic solution to the problem of laminar flow within a pipe (circular Poiseuille flow) do exist and results in a parabolic velocity profile.[46] The point being that even when the flow is turbulent the mean velocity is still too small a value to represent the actual velocity within the center of the pipe. On the initiative of Michelson-Morley[47], both Lahaye and Maers[48] chose to multiply their velocity values by 1.165. Fizeau himself also argued that the mean velocity was too small and therefore multiplied his data with values around 1.15. And seeing as the cool kids does it, I must also try it at least once. In Figure 32 I have plotted the mounted data $\Delta\phi_{result}$, this time as a function of the new velocity $u_{new} = 1.165 \cdot u$. The result is a new slope, see Table 4.

Table 4: The experimental results for when taking the turbulent flow in to account.

	Experimental slope	Relativistic slope	Classical slope
Mounted, u	0.029 ± 0.004	0.025	0.056
Mounted, u_{new}	0.024 ± 0.003	0.025	0.056

4.6 Result and Discussion

The experimental result of the reenactment for Fizeau's aether drag experiment can be found in Table 4, visually represented in Figure 32. As I mentioned earlier this result is the outcome of a test to see if a mounting of the corners and mirrors would result in a more stable set of data. The mounting method was quite crude and because of the crudeness and the need to repeat this result I will not claim this experiment as a confirmation of the theory. However I cannot deny that I feel very happy about the result especially because the prediction of the slope made by the special theory of relativity (SR, equation (4)):

$$\Delta\phi_{SR} = 2L\frac{1}{\lambda \cdot c}(n^2 - 1) = 0.025 \tag{5}$$

[46] [10] pp. 315.

[47] [14] pp. 384

[48] [13] pp. 301

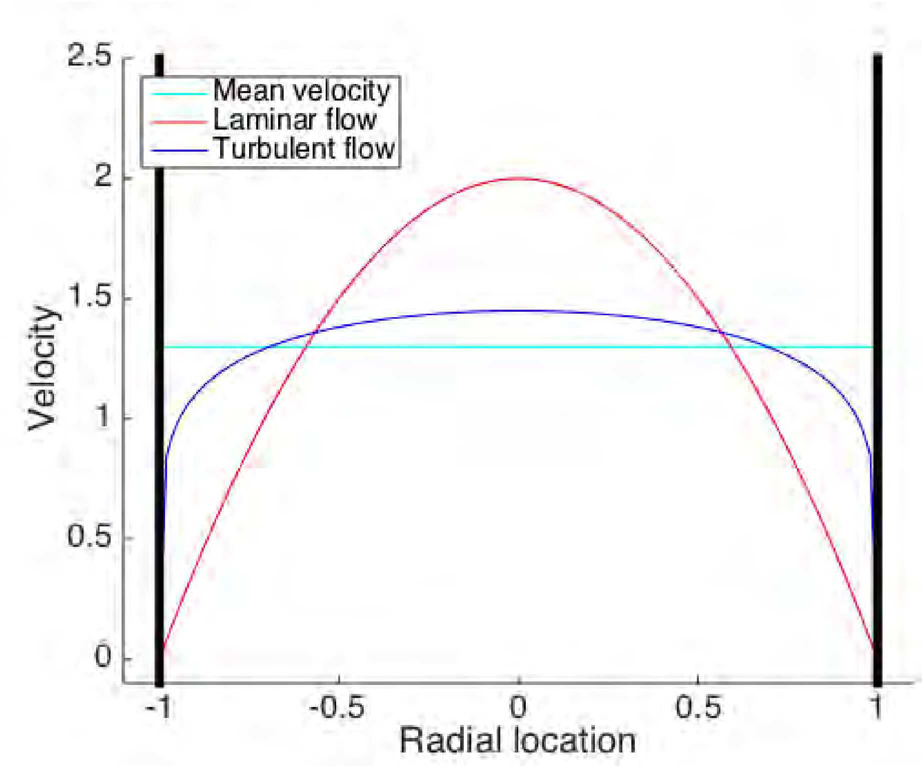


Figure 31: Arbitrary velocity profile for water flowing through a pipe.

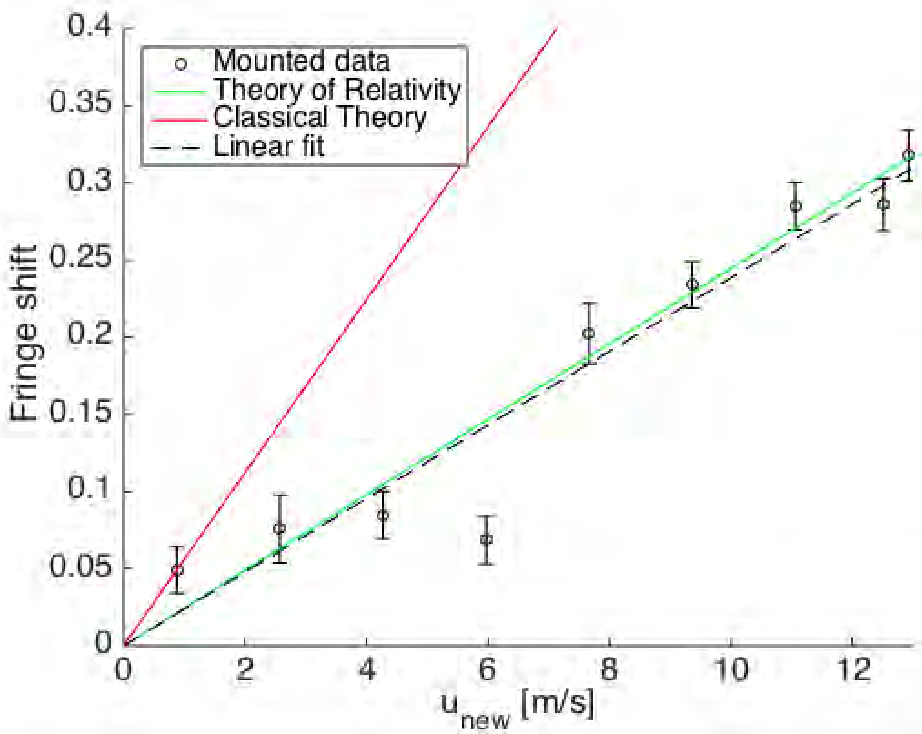


Figure 32: The experimental result of the mounted setup with the changed velocity $u_{new} = 1.165 \cdot u$.

actually lies comfortably within the standard deviation of the experiment

$$\Delta\phi = 0.024 \pm 0.003.$$

One of the reasons why I still feel there is a strong need for duplication of the result, preferably with a proper mounting system, is the one data point that diverge from the rest. I believe this to be a result of some sort of shift in the mounting system and therefore believe it would not reemerge when the experiment was duplicated. I would of course like to see a proper mount manufactured and preform the experiment again myself, but as my time on this project has run out I must leave this to the next person who takes an interest in the setup. Further improvements of the setup is suggested in section 4.7 below.

It is important to note that the purpose of this thesis has never been to produce a competitive experiment which with high accuracy could perform the Fizeau experiment. The purpose always was to produce a mobile demonstration experiment which could show the properties of the Fizeau experiment in front of an audience in an auditorium. I believe this goal was achieved already before the crude mounting system was introduced, but will especially come in to effect after a proper mount has been produced.
The reason this setup is functional and still mobile is mainly due to the improvements done to the water flow system. An important requirement of success was to reduce the vibrations from the pump enough to let the interferometer work properly. By moving the narrowing closer to the pump and removing the 90 degree corners, off the table mounted flow system, this was achieved. Another important improvement was the introduction of the frequency controller which now controls the velocity of the water. The converter obviously makes it possible to get data points at several velocities which gives a better set of data but more importantly, as this is a demonstration experiment, it enables real time manipulation of the interference pattern due to relativistic effects. The effect of this mobile relativistic experiment is easily observed via the data projection screen which also doubles as a data collection screen. The webcam enables the data to be blown up via a projector and thereby letting an entire audience witness special relativity in action.

Experiments of similar accuracy have been performed two times within the last couple of years, once at the University of Toulouse in France[49] and once at the Cornell University in USA[50]. The two experiments were preformed using the same way of collecting data, that is, by looking at a section of about ten interference bands and fitting a sinusoidal function to the data. As I mentioned earlier a possible hazard of this way of collecting data, is that a possible displacement of the laser dot would be added to the interference shift without one noticing. In my case the curvature probably was the result of this extra displacement but one can imagine a different setup would not introduce such a curve and simply just alter the measured slope. The people at the University of Toulouse measured the desired effect but the people at Cornell University end up concluding the observation of the Doppler effect (their data can be found in Appendix A, Figure 44). I suspect that the people at Cornell University actually experience an extra shift due to a displacement of the entire laser dot which then leads them to conclude differently than Fizeau, Michelson-Morley, Lahaye and I.

4.7 Future Improvements

As I have mentioned a couple of times by now, the next step in the development of this setup will have to be a proper mounting of the corner/window sections. The problem of the windows shifting is primarily at the entrance and the exit of the table mounted water flow system as the other two corners are connected and thereby mounted more firmly. Upon my crude mounting of the entrance and exit corner/mirrors I fastened the corners (Figure 41) due to practicality but I will recommend fastening the mirrors directly as this will ensure no impact on the window as a result of force exerted on the corners. I have learned that when needing this type of problem solved the engineers and technicians at the metal work shop always have a excellent overview of the implications of producing experimental setup. That is why I always consult them early in the developing process as the result often is much better than if I myself tried to design the part.
The blur of the interference pattern at low water velocities has been a cause of some frustration throughout this project. As mentioned earlier I have tried various things to solve the problem, but with no luck. However I have realized that this type of closed water

[49][11]
[50][13]

system placed in a room of about 20°c is bound to produce some sort of biological life from. When consulting a friend of mine who study biology he referred to this problem as a case of biofilm, which simply means that a sort of algae have formed within the system, mainly placed at all the surfaces. Seeing as the biofilm is loosely attached to all the surfaces it clearly remains within the system even through one changes the water, also if it is changed to demineralized water. As when keeping a pool, where the pH value is controlled to prevent algae to form, we must add chlorine to the water. I have had no time to test if this solves the problem of the blur, but even if it did not, I would still recommend adding some chlorine to the mix for hygienic purposes.

In order to produce a greater shift in interference bands one could do various obvious things. By looking at equation (5):

$$\Delta\phi_{SR} = 2L\frac{1}{\lambda \cdot c}(n^2 - 1) = 0.025$$

one quickly realizes that a number of relatively simple changes can cause a greater slope and thereby achieve a greater shift at the same velocity. First thing I would do was to get a laser with a lower wavelength. A green laser ($\lambda_{\text{green}} \approx 530nm$) would be easy to get and is great in a demonstration experiment as the human eye is extra sensitive to the color green, but if one really wanted to maximized the shift a blue laser ($\lambda_{\text{blue}} \approx 450nm$) is the way to go. It is important however to make sure, the coherence length of the laser is a couple of meters. Another obvious change is to lengthen the distance the light travels within the water. The table of the setup actually allows two pipes which is about 20cm longer. A change to a blue laser of wavelength $\lambda_{\text{blue}} = 450nm$ and longer pipes $\mathrm{L}_{\text{Long}} = 1.9\text{m}$ would give the new slope (Figure 33):

$$\Delta\phi_{SR,\text{optimized}} = 2L_{\text{Long}}\frac{1}{\lambda_{\text{blue}} \cdot c}(n^2 - 1) = 0.043.$$

Which for a velocity of 11m/s would give a displacement of $\Delta\phi_{SR,\text{optimized}}(u = 11\text{m/s}) = 0.48$, compared to $\Delta\phi_{SR}(u = 11\text{m/s}) = 0.27$ which is quite a large improvement.

Another way to get a larger band displacement would be to gat a higher velocity of the water. This is in fact possible for this setup but not without loosing the mobility. The frequency generator sets out at about 46Hz which I believe is because the outlet does not allow more power. However both the frequency generator and the pump functions at up to

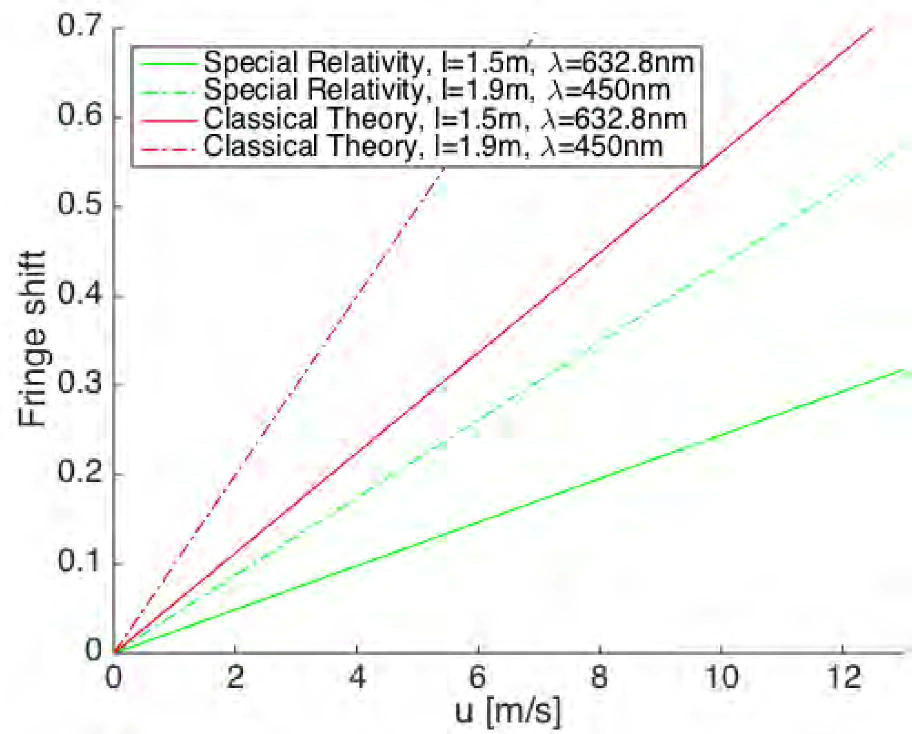


Figure 33: Graphical representation of the slope when extending the pipes and using a laser with a shorter wavelength.

60Hz which I believe could be achieved by changing the plug to work with a 400V power outlet. This change would however require a 400V power outlet in the room in which the experiment was carried out, and since few auditoriums have those, it would limit the mobility of the setup.

When i preformed the experiment i chose to set it to about four interference bands in order to let the displacement be visible to the naked eye, as the velocity of the water is varied. However I believe a greater accuracy could be achieved by collecting data over more bands. The above method using an envelope function can still be used with more bands, but once the windows have been properly mounted I expect the method of Lahaye will work just as good and with simpler data processing needed.

If I could redesign a part of the setup it would be widening the pipes that leads from the corners to the windows. There is no need for these pipes to be smaller than the pipes in the rest of the system and the only thing achieved by this difference in inner diameter is a lot of hassle when aligning the interferometer. I believe the reason for the smaller pipes could have something to do with the amount of turbulence a larger pipe would cause but

I do not believe this to be a genuine problem.

Lastly if the table mounted water flow system is taken apart at some point, I would recommend that the end of the pipe, which leads to the window, should be milled down a couple of millimeters as I have broken a couple of windows when sealing them in.

5 Construction

The construction of this setup is simple and can be done rather inexpensively.

5.1 Water Flow System

The water flow system can be built out of equipment from the local hardware store and instead of using an industrial grade pump one can simply use water straight from the faucet. I have tested the water flow from a faucet in the cellar of the physics department at Aarhus University to be $Q_l \approx 0.19$liters/s. If I were to do the experiment with a tube with an inner diameter of d=8mm, the water velocity would be

$$v = \frac{Q_l}{2\pi(d/2)^2} = 3.8\text{m/s}.$$

If the tube was L$= 2 \cdot 1.5$m and the laser green ($\lambda = 530nm$) one could expect to see a interference band shift of about $\Delta\phi \approx 0.22$.

I have checked the prices on the plumbing equipment needed to build the flow system and an estimation of the price along with a list of the individual pieces need can be found in Table 5.

Table 5: List of components needed when building the water flow system from hardware store plumbing articles.

Component	Individual price [dkk]	Quantity	Price [dkk]
Cobber pipe, 5m, Ø8mm	139	1	139
Tee pipe	13	4	52
Pipe mount	24	10	240
Transition pipe	16.5	4	66
Cap nut	8.5	4	34
Manometer	23.5	1	23.5
Garden hose	60	1	60
Hose clip (5pcs.)	16.5	1	16.5
Total			631

Personally I would make the windows myself as they can be rather pricy when bought at an optics company such as `edmundoptics.com` or `thorlabs.com`. I would then drill a hole in each cab nut and mount the windows with a silicon based glue. The equipment needed to build the water flow system is easy to get and also quite inexpensive at the total price of less than 700dkk.

5.2 Interferometer

Buying the equipment for an interferometer can be rater expensive and I recommend teachers to check if their place of work already have the necessary components such as beamsplitters and mirror mounts. Schools sometimes have optical kits which contain all the components necessary to build an interferometer. If one does not have the components needed, I have put together a short list of necessary things, along with price tags from `thorlabs.com`, in Table 6. The shopping list is based on the setup depicted in Figure 34.

Table 6: List of components needed when building an interferometer.

Component	Individual price [US$]	Quantity	Price [US$]
Mirror	10	3	30
Kinematic mount	40	3	120
Beamsplitter	150	1	150
Beamsplitter mount	55	1	55
Lens	30	1	30
Lens mount	15	1	15
Optical post (5pcs)	25	1	25
Post holder (5pcs)	35	1	35
Post holder base (5pcs)	26	1	26
Laser mount (V-clamp)	38	1	38
Total			524

As of the choice in laser, a simple green 5mW laser pointer should do the trick. A way of making sure the laser is stable enough, to use in an interferometer, could be to build a Michelson Morley interferometer (Figure 35), which is easy to set up and align. One could simply make each of the ”arms” the length we expect the laser beams should travel through our sagnac interferometer, and see if the interference pattern is clear cut and stable. Such a laser pointer can be purchased on eBay for 5US$ which is also the price for an USB webcam. All together the price on an interferometer sum up to about 3500dkk.

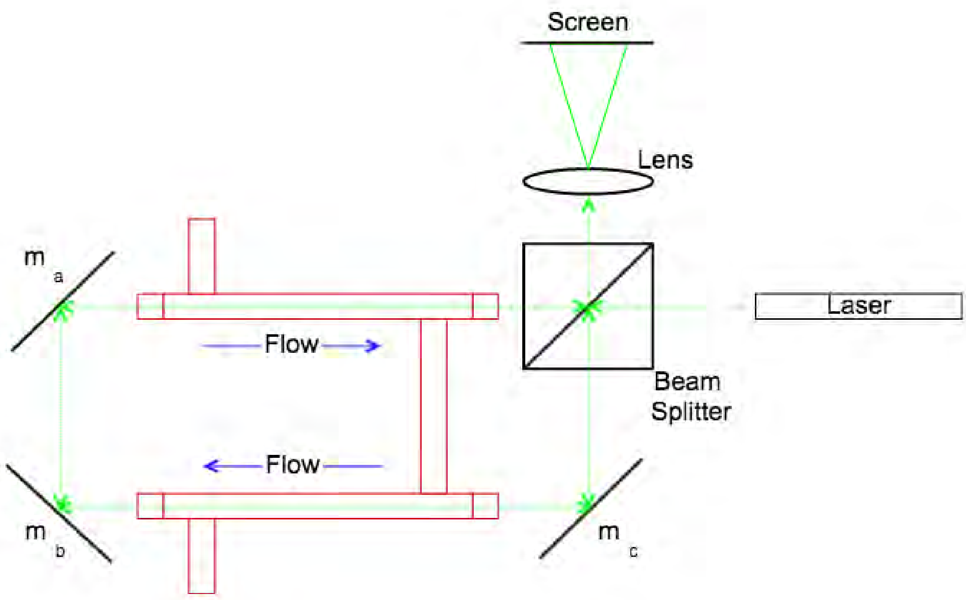


Figure 34: An alternative setup containing a sagnac interferometer with the minimum amount of hardware needed.

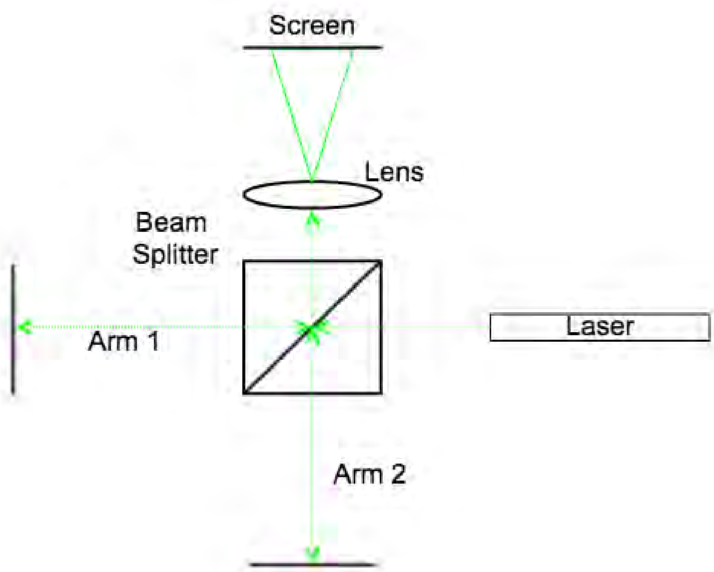


Figure 35: A diagram of a Michelson Morley Interferometer.

5.3 Assembly and Alignment

When assembling this setup it is of course important that the water flow system is properly mounted, but especially that the windows at each end of the long pipes are mounted firmly. I do not think vibrations will be a problem when using a faucet as a flow source but if it is then make the garden hose, which run from the faucet to the setup, a bit longer. As there is bound to be a difference in pressure through the pipes of the setup I recommend checking the water flow Q again after assembly, since it might be a bit smaller.

I recommend that the alignment of the interferometer is done before the cab nots, containing the windows, are mounted, hence with no water in the system. This makes the alignment easier and you are sure that if a problem emerges, once the water is introduced, the alignment is not to blame. Adding the windows can cause a little displacement of the beams so keep the interferometer on when mounting them. I had a small problem of air bubbles close to the windows which was solved by letting the water flow while softly loosening a cap nut till water spilled out, thereby also letting out the bubbles. Once the setup is up and running you can make sure the windows are properly mounted to the table, by a applying a bit of pressure to the cap nuts in different directions. If the interference pattern moves the windows are not properly mounted.

6 Didactic Reflections

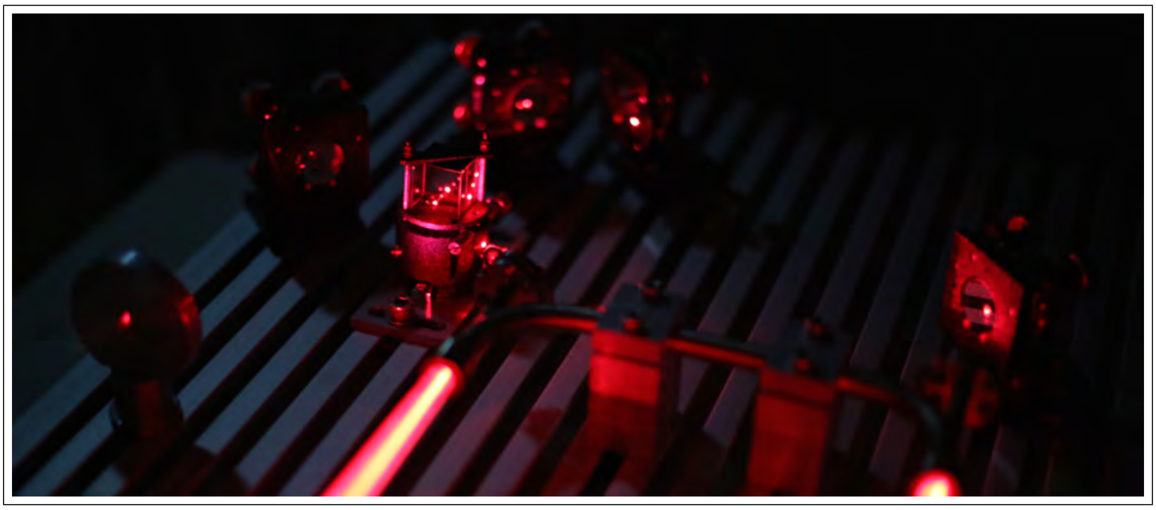


Figure 36: Photograph showing the visually appealing nature of the setup.

This take on the Fizeau aether drag experiment was designed and constructed to be a demonstration experiment. But what makes a good demonstration experiment and why is the Fizeau experiment qualified to become one?

Wether giving a lecture in front of a hundred people or teaching a class of thirty pupils one has to be aware of the same things when performing a demonstration experiment. The setup preferably should be simple and easy to control and the teacher must not use too much time getting it started in front of the audience. Once the experiment is up and running it should show the desired tendencies within a short time period or it should be able to run in the background while the teaching continues. It is imperative that the entire audience can see what is going on otherwise the demonstration becomes indifferent. The best demonstration experiments are often quick to perform and the point is very clear from the results. Furthermore there is easy credits to be made from the audience if the demonstration is visually appealing and it has some sort of wow effect.

Experiments that show relativistic effects are often time consuming or large and sometimes both. In comparison the Fizeau experiment is, in our case, small and mobile plus the execution of the experiment is simple and swift. The simplicity of the setup makes the result easier to comprehend for the layman compared to experiments of cosmic decay or

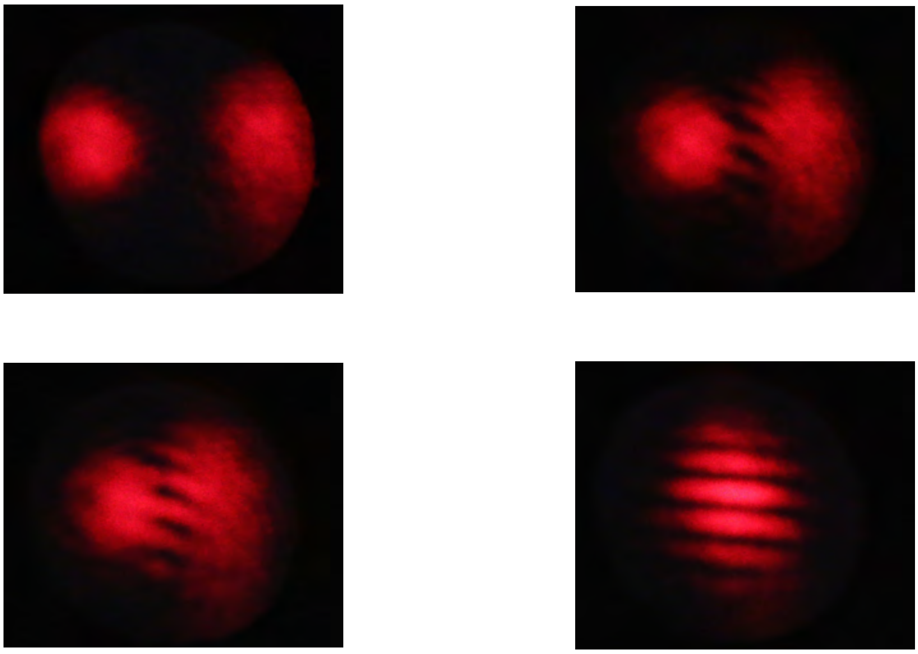


Figure 37: Photographs of the data screen upon superposing the two laser beams to obtain the interference pattern.

the scattering of electromagnetic radiation. The fact that most of the setup can be bought in the local hardware store makes the experiment rather unique, as far as relativistic experiments go. To my knowledge it is the only relativity experiment that can be performed at home on the kitchen table.

As Figure 36 and the front page of this thesis illustrate, the setup is visually quite stunning when the lights are dimmed. Even though this has little to do with the actual experiment the fact that it looks good is a definite advantage when doing the demonstration. I chose to use the data collecting screen (Figure 4) because it makes the experiment more approachable, compared to the method of Lahaye, there is in fact no need to put a computer monitor between the spectator and the experimental result. As the frequency converter controls the velocity of the water it is possible to see the properties of relativity simply by turning a knob. The special theory of relativity unfolds right in front of the spectators eyes in real time.

If one were to perform this demonstration in front of an audience at upper secondary school level, several other subjects than the theory of relativity could easily be treated. To understand the experiment it is important to understand the wave nature of light and the superposition principle, hence a treatment of this subject could easily accompany the demonstration. Figure 37 contains a series of photos from the setup, that demonstrate the wave nature of light by interference. Furthermore an understanding of turbulent versus laminar flow can be an interesting extension of the experiment. When calibrating the water velocity, according to the frequency of the frequency converter, I found that at very low velocities one could observe laminar flow. I shot a short video of the phenomenon which can be found via Figure 38. In the video you se impurities in the water moving in a straight line and it travels faster closer to the middle of the tube.

Figure 38: Video of laminar flow at water velocity close to zero. Recommend watching this video on a larger screen. The video can be found via the following link as well: `goo.gl/x8uJ9T`.

This reenactment of the Fizeau experiment will do great as a demonstration experiment. Both the simplicity but also the history of the experiment will make it interesting to an audience and the transparent tubes makes it a great visual experience. One downside to the setup is the noise the pump makes at high velocities, but one should keep in mind that there is no need for the pump to be going at full throttle for more than a couple of seconds.

7 Video presentation

I have produced a set of videos which give a short insight into the setup. The first video (Figure 39) briefly explains the historical context of the Fizeau experiment while presenting the setup and the result in Figure 32. The second video (Figure 40) only presents the setup and the result. The following section contains the manuscript of the first video.

Figure 39: QR code which links to a video containing a short presentation of the historical context of the Fizeau experiment along with a short presentation of the setup and the result of Figure 32. Alternative to QR code, link: `goo.gl/oNVOPf`.

Figure 40: QR code which links to a video containing a short presentation of the setup along with the result of Figure 32. Alternative to QR code, link: `goo.gl/bw2kiv`.

7.1 Manuscript

In 1905 Albert Einstein published the paper that would earn him the title as father of the theory of relativity. However, few people know that 50 years before a french physicist named Hippolyte Fizeau preformed an extraordinary experiment that would influence physics throughout the century even though it was not properly explained until Einstein wrote his 1905-paper. Einstein himself later stated that "the experimental result which had influenced him most were the observations of stellar aberration and Fizeau's measurements".

Now.. Lets take a look at the experiment!

Explain the setup

A peculiar thing about Einstein's paper is the title: "On the Electrodynamics of Moving Bodies". This title doesn't exactly tell you that this is the paper that marks the start of the theory of relativity does it? Never the less the title makes good sense when put into a

historical context. The electrodynamics of moving bodies was ”the” field to research at the turn of the 20th century and a prevailing theory had to account for the experimental result of Fizeau.
Even the title of Fizeau’s 1851 paper ”On the Effect of the Motion of a Body upon the Velocity with which it is traversed by Light” seems as a breadcrumb which leads to Einstein’s paper: ”On the Electrodynamics of Moving Bodies”.
So there you have it. The Fizeau experiment: a relativistic experiment 50 years before the theory of relativity emerged.

7.2 Director’s Commentary

Upon rewatching the video I have found a single phase which I feel i must explain further. I the first video, and in the above manuscript, I utter that the Fizeau Experiment was not ”properly explained” until Einsteins 1905-paper. This statement might be a bit strong as the Maxwell equations also explain the result. What I mean by the statement is that the simplicity with which the special theory of relativity explain the Fizeau measurements makes it the ”go-to” explanation from this point on. Thereby making it the proper explanation in the eyes of the modern physicist. Furthermore I am aware that the Fizeau experiment was not explained by the theory of relativity until 1907 when Max von Laue did it, but for the sake of simplicity I allowed myself this simplification.

8
Conclusion

As planned I have set the stage of which the Fizeau experiment came to influence physics in the second half of the 19^{th} century and through the turn of the 20^{th} century. The work of Fizeau was inspired by Fresnel's partial ether drag theory which was developed to explain Arago's 1810 experiment. At the turn of the 20^{th} century few physicist believed Fresnel's theory but never the less a possible new theory had to account for Fizeau's result. Lorentz explained the experiment through his new theory of electrons by introducing the concept of local time. The work of Lorentz and specifically the work containing the Fizeau experiment inspired Einstein in his development of the special theory of relativity. I have made a set of improvements to the ten year old setup most importantly the new placement of the narrowing, which reduced the vibrations on the table considerably, and the introduction of the frequency converter, which with accuracy can control the velocity of the water hence giving the possibility for detailed data sets. After making a short series of experiments, it was obvious that the physical principles of the Fizeau experiment was at work. However it is also obvious that some further improvements has to be made. I am confident that a fastening of the windows will result in a much better set of data since my crude mounting already showed great potential.
The didactic advantages of the setup are numerous and once it is finished it will be a great contribution to a lecture given on the special theory of relativity. One can easily, and on a low budget, purchase the components necessary to build the Fizeau experiment. With a little technical ingenuity this setup can easily be a part of teaching in the upper secondary schools and if functional it can be included in senior projects.
I have furthermore made two short presentation videos which give a short insight into the setup and the history surrounding the the Fizeau experiment.

It has been a great pleasure to work on this project, as development of the experiment has demanded a good sense of experimental technique both within the area of special relativity but also in the practicalities of designing and redesigning an experiment. The Fizeau experiment truly is quite ingenious in it's simplicity and wondrous in it's application.

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Appendix A - Pictures

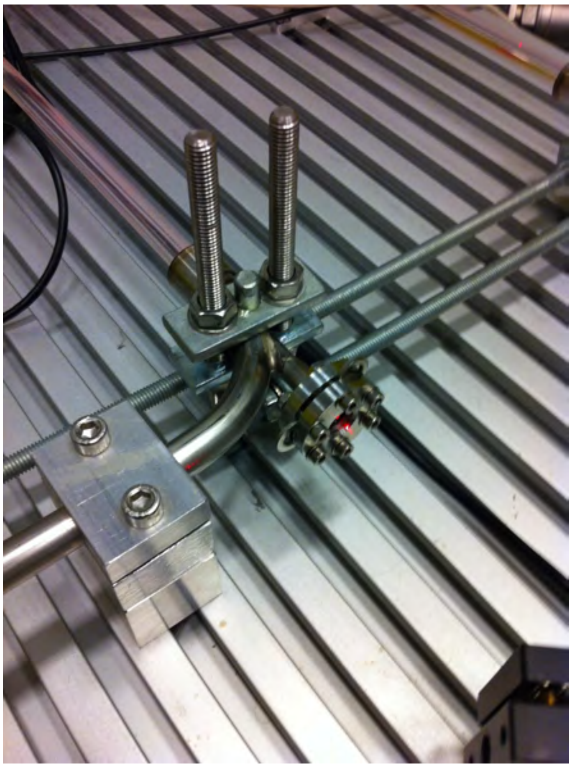

Figure 41: The temporary crude mounting system, entrance.

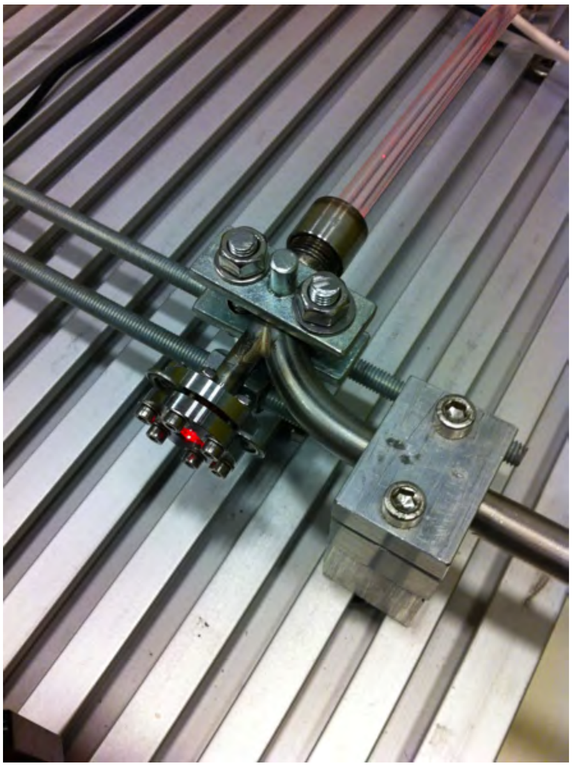

Figure 42: The temporary crude mounting system, exit.

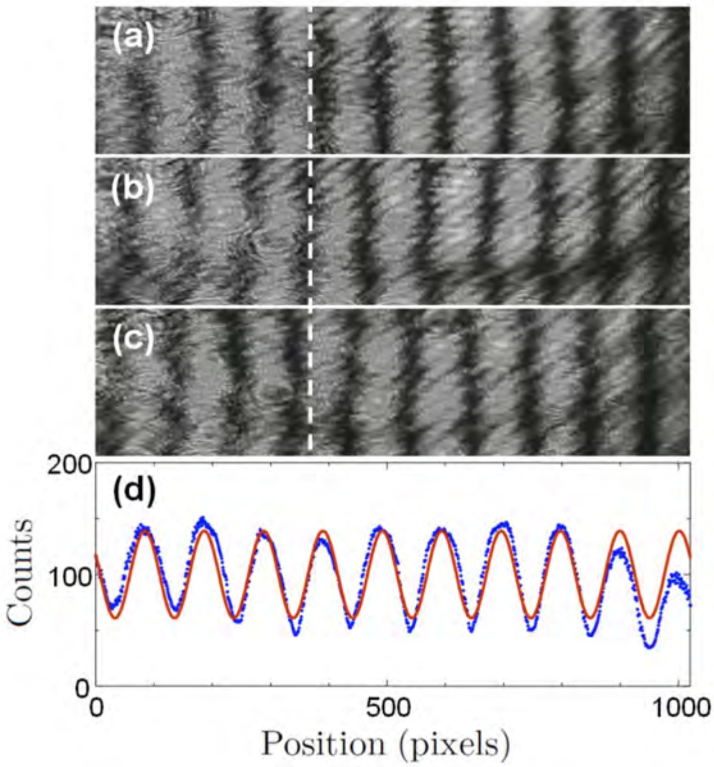

Figure 43: A picture of the data acquisition of Lahaye, borrowed from [11].

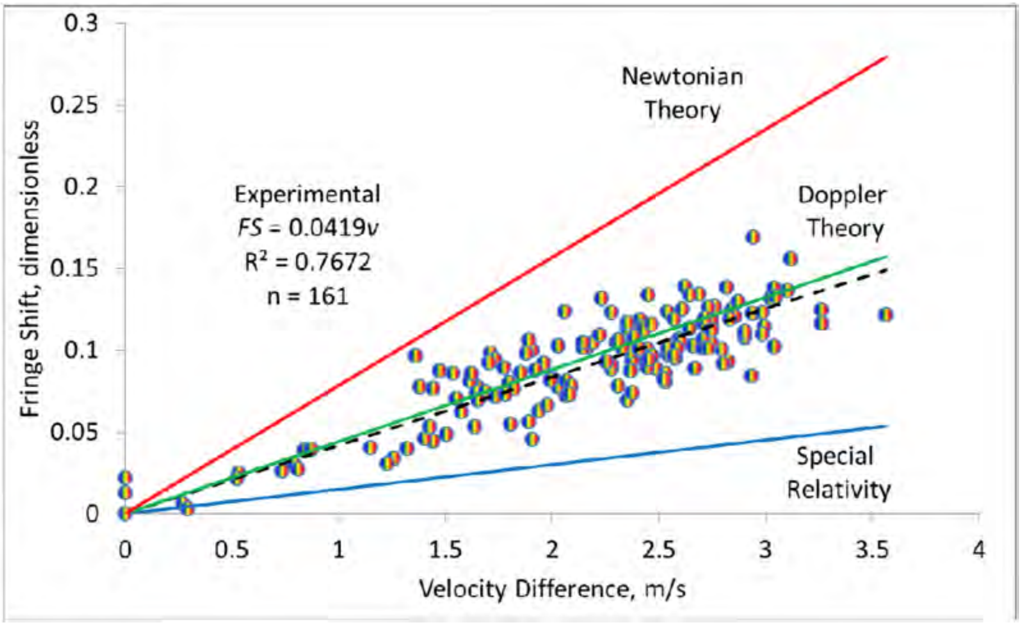

Figure 44: A picture of the data set of Cornell University, borrowed from [13].