

The Capabilities and Limitations of the Michelson Interferometer

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This experiment investigated interference phenomena using a Michelson Interferometer to explore calibration, beat frequency behavior, and spectral bandwidth. Using the known wavelength of mercury green light, 546.1 nm, we determined a conversion factor from displacement in the Micrometer Screw Gauge (MSG) to displacement in Mirror 1 (M1). By measuring an average of 6.74 fringes per 10 μm of MSG displacement, we determined a conversion factor of $1.84 \pm 0.24 \mu\text{m}$ of M1 displacement per 10 μm MSG displacement. Through this conversion factor, we were able to measure distances using the Michelson Interferometer, specifically the distances between beats in mercury yellow light. Across a range of 3,830 μm of MSG displacement, 10 beats were observed. With an average beat separation calculated, the wavelength separation of the mercury yellow doublet wavelengths could be determined. Our estimation of $2.31 \pm 0.31 \text{ nm}$ was within a reasonable range of the actual value of 2.11 nm. White light was then used with glass, green, and yellow filters to examine how spectral bandwidth affects fringe visibility. As predicted, broader spectral sources produced fewer visible fringes due to overlapping wavelength interference. These results demonstrate the capabilities of the Michelson Interferometer as a multi-purpose tool.

I. INTRODUCTION

The Michelson Interferometer is a crucial tool in optics used in many different ways, from measuring the diameter of stars to precisely measuring lengths. The instrument is designed to split light into two paths with a controllable difference in path length. The two separated beams will meet again and combine. Depending on the path length difference, interference patterns can appear as a result of the light waves' phase being off from one another. What we observe when this occurs is a pattern of bright peaks and dark 'fringes' where constructive and destructive interference occurs, respectively. Interference patterns also depend on the wavelengths of light that split. The more frequencies of light being split and recombined, the more interference we will observe due to the multiple wavelengths of light interfering with each other. Without knowing the specifications of a Michelson Interferometer, one must take into account the different scales and conversion factors that they are calibrated to. It is therefore important to know how to determine these parameters.

In this experiment, we will be studying the interference patterns made using the Michelson Interferometer. Through this we hope to further understand interference phenomenon and spectral bandwidth all while fully grasping the mechanics of the Michelson Interferometer. We set ourselves three objectives, first is to determine the calibra-

tion of our interferometer by using a single known wavelength. With changes in the path difference we will see the interference pattern shift which we can use to count how many wavelengths pass per change in the path. From that we can determine the conversion factor to study a phenomena occurring when two similar wavelengths are passed through an interferometer known as beat frequencies. This occurs due to the wavelengths interfering with each other going into sync causing the interference pattern to disappear. These 'beats' will help us estimate the difference between the two wavelengths. To further understand interference patterns we will look at light containing many different frequencies passing through our interferometer. These several different wavelengths interfere with each other the more the path difference increases causing the pattern to disappear at any path difference that is not very small. We should therefore expect that the more unique frequencies that are present, the smaller the range the interference pattern lasts. The results of this experiment will allow us to explore both the practical and theoretical aspects of optical interference, connecting our observations to fundamental wave principles.

II. APPARATUS AND METHODS

The Michelson Interferometer consists of a 45° beam splitter that transmits approximately 50% of the light and reflects the other 50%. The reflected

path travels to Mirror 1 (M1), which is mounted on a Micrometer Screw Gauge (MSG) that allows for precise control of its position. The transmitted path goes through a compensating plate, parallel to the beam splitter, before reflecting off Mirror 2 (M2). The compensating plate is used so that the transmitted light passes through the same amount of glass as the reflected light does, as seen in Fig. 1. The tilt of M2 can be adjusted to modify the appearance of the interference pattern, allowing transitions from circular fringes to linear ones depending on its alignment. Because the light is reflected back to the beam splitter, any motion of M1 changes the optical path difference by twice that displacement. The smallest discernible unit on the MSG corresponds to $10\text{ }\mu\text{m}$. From this we must determine the conversion factor between movement in the MSG and M1.

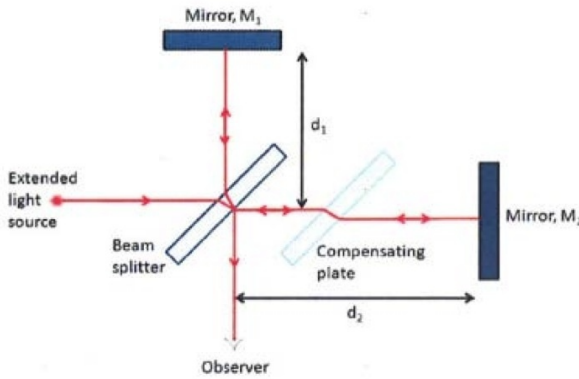


FIG. 1: The Michelson Interferometer. Diagram provided by the PHYS 4410 Confluence Page.

To determine this calibration, we used a mercury lamp with a green filter to isolate the 546.1 nm wavelength. By counting the number of fringes passing a fixed reference mark as the MSG was moved, we calculated the path change per unit MSG displacement. Each fringe corresponds to a path difference of one wavelength.

Using a yellow filter, we can focus on the interference pattern of the mercury yellow doublet wavelengths that have an average wavelength of 578 nm . These wavelengths have a small wavelength separation which allows us to observe the beat frequency phenomena. With our conversion factor, we can determine the distance between these ‘beats’. The following equations and approximations were used to determine the wavelength

separation for the mercury yellow wavelengths:

$$\lambda_{beat} = 2 \cdot (\text{scale factor}) \cdot \lambda_{MSG\ Beat} \quad (1)$$

$$\Delta\lambda = \frac{\lambda_1 \cdot \lambda_2}{\lambda_{beat}} \approx \frac{\lambda_{avg}^2}{\lambda_{beat}} \quad (2)$$

where λ_{beat} is the measured mirror displacement between beats and $\lambda_{MSG\ Beat}$ is the beat displacement for the MSG.

Mercury light provides a great source for singular wavelength light source and a double wavelength light source, but white light provides a source of many more unique frequencies. We will use the white light under a glass, green, and yellow filter to understand how the amount of different frequencies present affects the interference pattern. We predict that the more unique wavelengths present, the smaller the range will be for when the interference pattern is present. Physically we should see this as less fringes appearing for smaller ranges of the inference.

III. RESULTS AND DISCUSSION

The results for the conversion factor were calculated as an average of several trials of counting fringes per MSG movement. Our plots are demonstrating potential sources of error that could have arisen from our setup. Over the course of the 10 trials we took, the average number of fringes passing per $10\text{ }\mu\text{m}$ of MSG displacement was 6.74. We used two different methods for counting fringes, prioritizing MSG displacement and prioritizing fringes. Because we were counting fringes passing a point with our eyes only, it was difficult to prioritize counting MSG displacement while keeping track of fringes. Prioritizing fringes counted while reasonably estimating MSG displacement was much simpler and overall more precise.

Another potential source of error was in the consistency of the MSG. We tested this by checking the linearity of MSG over the small range we conducted our trials. Fig 2. shows the amount of fringes counted in a range of MSG positions. From this figure we concluded that the MSG seems for the most part linear with most sources of error stemming from human error.

One way we demonstrated potential human er-

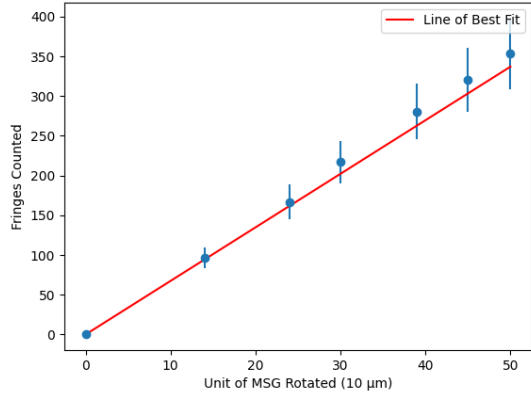


FIG. 2: Linearity in the Michelson Interferometer. Total fringe counts plotted for intervals of MSG displacement, where 1 unit = 10 μm of displacement. Red line represents the average fringe count per unit plotted

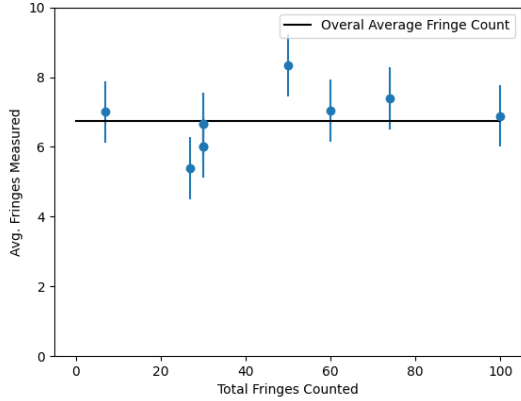


FIG. 3: Correlation between higher fringe count and average fringe. Each trial is plotted with error bars being the Std. Dev. Black line represents the overall average value.

ror was in testing how the amount of fringes counted in a trial influences the average number of fringes per MSG displacement. Fig 3. plots the different averages calculated based on the total number of fringes counted to calculate the average with the straight line representing the overall average amount of fringes per 10 μm of MSG displacement. The biggest discrepancies between the value measured and the average came from when we did measurements of around 20-50 fringes, but after a certain point the values calculated were much closer to the average. This is due to small human errors in a final fringe count mattering less for averages over larger fringe counts. Given these

potential sources of error, using the standard deviation of our set of averages ends up being a reasonable numerical estimation for error as the potential systemic error seems minimal compared to the human error. The standard deviation ends up being around 13.2% of our final value. With this overall average we can convert to the total change in path length per 10 μm of MSG displacement. Dividing this number by a factor of two gives us our final conversion factor of 1.84 μm of M1 displacement per 10 μm of MSG displacement with $\pm 0.24 \mu\text{m}$ of error.

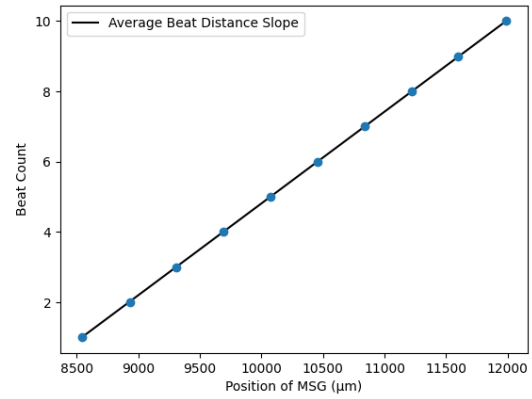


FIG. 4: Beat Detection Plotted. Plot of each MSG position where beat was found. Black line has the average beat separation as a slope. Error bars are almost negligible at this scale

In Figure 4 the incident of every beat observed in the mercury yellow lines is plotted, with the entire set of data observing 10 beats over the course of 3,830 μm of MSG displacement. Therefore the average distance between beats was 383 μm of MSG displacement. Using Equation (1), this number is converted to 141 μm of M1 displacement. Figure 4 also provides another sanity check for possible mechanical errors by showcasing the linearity of the MSG. The data shows that each beat was roughly equidistant from each other meaning that the MSG has no noticeable non-linearity. Despite this, beats in mercury yellow are difficult to precisely detect. A beat is recorded when the fringes disappear completely, but with the human eye it is difficult to be certain when exactly the fringes completely disappear versus when they mostly disappear. All data points either had a distance between beats of 380 or 390 μm , which we can attribute to limitations in our human eyes.

Standard deviation was the best numerical esti-

mation for error in our measurements since majority of the error was due to uncertainty of where the beats were precisely. Our standard deviation was 1.2% of our measure value, which pales into comparison with the error from our conversion factor, 13.2%, therefore the total error in our beat wavelength and wavelength separation is 13.3%. Using the approximation in Equation (2), the wavelength separation calculated is 2.31 ± 0.31 nm. With the actual value being 2.11 nm, this falls within our range of error calculated. Due to the majority of that error being coming from our conversion factor, to compensate we would need to have measured a greater conversion factor. This checks with our theory that human error is the cause for the majority of the error as under counting fringes is likely why our conversion factor is too low.

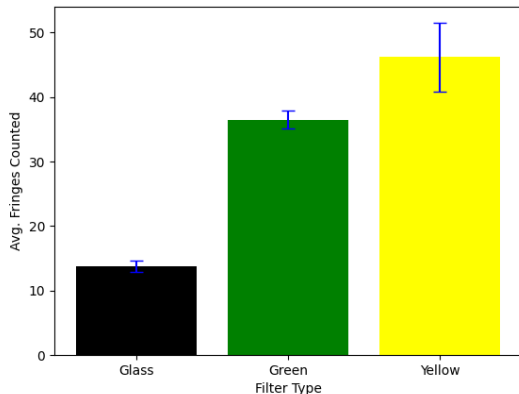


FIG. 5: Avg. Fringe Count for White Light through Different Filters. Plots the amount of fringes visible for white light through a glass, green, and yellow filter. Error bars are in blue.

For the white light results there was difficulty finding the interference pattern as expected. At around an MSG position of 16,860 μm would the interference pattern appear for the white light. Depending on the filter used this range would increase but would be centered around the same point, which is when the path difference between M1 and M2 was zero. Figure 5 demonstrates the average amount of fringes that would appear for each filter with the glass filter showing 13.8 fringes on average. The green and yellow filters caused many more fringes to appear, on average 36.5 and 46.2 fringes respectively. The reason for this is due to the filters blocking out more frequencies than a glass filter, which causes there to be less interference allowing there to be more fringes to appear

before disappearing. The yellow filter showed the most fringes which implies that the light is made up of more green frequencies than yellow ones. Because the fringes disappear slowly it could be difficult to exactly count when they start appearing, especially for the dim yellow light.

This data represents the bandwidth of the white light for the different filters. Smaller bandwidths correlate to large fringe counts. Each average fringe count for a filter has its own error depending on the standard deviation of the 10 trials. While it was easier to detect when the fringes disappeared for the glass filter, its smaller fringe count caused small differences in fringe count to give us a higher error percentage than when using the green filter. The green filter had a much higher fringe count with roughly the same clarity as glass filter, therefore its error percentage was much smaller. The dimness of the yellow light caused a lot of inconsistencies when measuring fringe count and despite its overall largest fringe count, it had the highest error percentage.

IV. CONCLUSION

Our experiment demonstrated the possibilities and limits of the Michelson Interferometer with respect to investigating interference phenomena and understanding spectral bandwidth. By using the mercury green line, we were able to calibrate the Interferometer so that a conversion factor could be used for future measurements. Due to the importance of this conversion factor, the potential sources of error from the interferometer was investigated. We concluded that the majority of error stems from human limitations as the only detector available was our own eyes. A future experiment could limit this error through the use of a camera that can record the fringes passing. This would reduce the possibility of undercounting any fringes giving us a more accurate conversion factor. With respect to studying the interference phenomenon of beat frequencies, the interferometer proved to be a useful tool for measuring the wavelength separation that causes beat frequencies. The exact value ended up being within our error range for measured wavelength separation of the mercury yellow wavelengths. The small offset is likely due to the aforementioned error stemming from our conversion factor. Our final

objective of observing spectral bandwidth was a success. We noted that filters with larger spectral bandwidth demonstrated smaller fringe counts than those with smaller bandwidths. In the case of white light through glass, green, and yellow filters, the bandwidths would decrease accordingly. We can take away from these results that smaller bandwidths provide greater “detail”, more fringes

visible, but at the cost of losing frequencies of light. Whereas higher bandwidths provide less detail but compensate with having a larger variety of frequencies. With bandwidths being crucial in data transfer, using the Michelson Interferometer provides a greater understanding of the benefits and limitations for different spectral sources in terms of bandwidth.

[1] Jenkins and White, "Fundamentals of Optics", Ch. 13

[2] Department of Applied and Engineering Physics Cornell, O-2 Michelson Interferometer, Confluence (Mar. 17, 2025)