THE ART OF OPTICAL ABERRATIONS

by

Clarissa Eileen Kenney Wylde

A Thesis Submitted to the Faculty of the

COLLEGE OF OPTICAL SCIENCES

In Partial Fulfillment of the Requirements

For the Degree of

MASTER OF SCIENCE

In the Graduate College

THE UNIVERSITY OF ARIZONA

2017

STATEMENT BY AUTHOR

This thesis titled *The Art of Optical Aberrations* prepared by Clarissa Eileen Kenney Wylde has been submitted in partial fulfillment of requirements for a master's degree at the University of Arizona and is deposited in the University Library to be made available to borrowers under rules of the Library.

Brief quotations from this thesis are allowable without special permission, provided that an accurate acknowledgement of the source is made. Requests for permission for extended quotation from or reproduction of this manuscript in whole or in part may be granted by the copyright holder.

SIGNED:________________________________

Clarissa Eileen Kenney Wylde

APPROVAL BY THESIS DIRECTOR

This thesis has been approved on the date shown below:

____________________________	5/5/17
José Sasián Professor of Optical Sciences and Astronomy	Date

ACKNOWLEDGEMENTS

Without the help and encouragement of numerous people, this thesis and the ensuing exploration into my passion of combining the arts and sciences would not have been possible. To all of you, I am extremely grateful.

Over the years, many professors have played huge roles in helping me achieve this dream. I am especially thankful to my advisor in the College of Optical Sciences at the University of Arizona, Dr. José Sasián, for believing in me, being patient with me, and expressing excitement for this new direction in combining optics and art. Thank you also to my committee members Dr. Jim Schweigerling and Dr. Russell Chipman for your enthusiasm with this project and all your suggestions. Furthermore, I would like to recognize my undergraduate professors at Biola University, Dr. John Bloom and Dr. John Silzel, for helping me realize my passion for optical physics and motivating and facilitating my out-of-the-box thinking. Finally, I would like to thank Kurt Simonson, MFA, Professor of Photography at Biola University, without whose guidance and encouragement I would have never started photographing interference patterns in the first place.

Additionally, I would like to thank Dr. Astrid Müller of the Beckman Institute at the California Institute of Technology for the inspiration to turn this research into a cutting edge presentation model. To my teacher friends and colleagues (Laura Evans, Kirsta Andrew, and Josh Watson) who helped me take this idea from conception to final product, I am greatly appreciative. Without your insight, knowledge, and creativity this idea would still be developing.

I would especially like to thank the Chemical Physics Laboratory at Concordia University in Irvine, CA for providing me with the laboratory space and all of the equipment to get this project on its feet. Additionally, I am grateful to Dr. Fred Johnson of California State University, Fullerton for equipping me with the fiber optic white light source. That apparatus was essential in getting the white light interferometric results I had envisioned. Without the generous donations of quality optical tables to the Chemical Physics Laboratory at Concordia, this work might not have been possible; for those, I would like to express my appreciation to the Chemistry Department at the University of Southern California. Furthermore, I would like to thank Ed Kane for his encouragement and tutelage in electrical engineering lab procedures.

To my fellow optics graduate students – I could not have done this without you! From the long late nights to the joyous successes, thank you for believing in me, encouraging me to be myself, and helping me along the way. I would especially like to thank Jessica Myers, Kelsey Miller, Krista Drummund, Gregory Jacob, Eric Herman, and Jeff Brown, as well as Amy Tso and Melissa Gutierrez.

To conclude, I would like to thank my family. My parents, John and Inga, have always supported me and been my biggest advocates on this journey. I am beyond grateful for the hours of time you both put into helping me and for your belief in me. Thank you also to my aunt Judy Pratt for your tireless and selfless nurturing. To my sisters, In-Laws, and all of my friends both near and far, I am very appreciative of your support. Finally, to my husband Travis, you have blessed my life more than words can express. Your constant encouragement through this whole process has made this a reality.

TABLE OF CONTENTS

TABLE OF FIGURES

ABSTRACT

Art and optics are inseparable. Though seemingly opposite disciplines, the combination of art and optics has significantly impacted both culture and science as they are now known. As history has run its course, in the sciences, arts, and their fruitful combinations, optical aberrations have proved to be a problematic hindrance to progress. In an effort to eradicate aberrations the simple beauty of these aberrational forms has been labeled as undesirable and discarded. Here, rather than approach aberrations as erroneous, these beautiful forms are elevated to be the photographic subject in a new body of work, *On the Bright Side*. Though many recording methods could be utilized, this work was composed on classic, medium-format, photographic film using white-light, Michelson interferometry. The resulting images are both a representation of the true light rays that interacted on the distorted mirror surfaces (data) and the artist's compositional eye for what parts of the interferogram are chosen and displayed. A detailed description of the captivating interdisciplinary procedure is documented and presented alongside the final artwork, CCD digital reference images, and deformable mirror contour maps. This alluring marriage between the arts and sciences opens up a heretofore minimally explored aspect of the inextricable art-optics connection. It additionally provides a fascinating new conversation on the importance of light and optics in photographic composition.

CHAPTER 1 – Introduction

Art and optics are inseparable. Though seemingly opposite disciplines, the combination of art and optics has significantly impacted the culture and science as it is now known. The pioneers of progress have never relied on one single aspect of knowledge or a single skill. It can be seen that innovative scientists and artists, regardless of field of study or medium, utilize a breadth of knowledge that might be categorically outside of their discipline. Some of the most brilliantly creative artistic minds are those doing laser or astronomical research. Likewise, some of the greatest scientific minds are those concocting new ways to take, develop, and print beautiful photographs.[1] Furthermore, since its inception in the early 1800s, the photography has served both science and art. The multifaceted aspects of the arts and also of the sciences are, more often than not, overlooked as the end products of great scientific research or artistic excellence are uplifted. Although many art disciplines employ multidimensional influences and expertise, those specifically intertwined with optical sciences are of special interest. Progressing in the same manner as the fields developed chronologically, a historical review of many light-based art forms from painting to cinematography is presented. Special emphasis is placed on the groundbreaking experimentation in the sciences by which these light-based art forms were shaped.

While scientific advancements have rocketed the various art forms into the future by opening doors to unbridled possibilities and thus to unbridled creativity, some aspects of progress have posed hindrances. The disciplines of photography and cinematography both heavily rely on technology developed in close association with the optical sciences. These two art forms both function by capturing light rays off of a subject at a distinct moment or a succession of moments in time. From subject to final product however, the light must be accurately transferred through various lenses, chemical encoding on film, digital encoding on CCD (charge-coupled device) chips or similar, enlargers, computers, printers, projectors, etc. Every time the light travels through a lens or interacts with other optical elements, either in the camera or in the various other steps to presentation such as enlargers or projectors, it has the potential to be deformed due to optical aberrations resulting in a degradation or perturbation of the final image quality and/or character. Optical aberrations are deformities in the wavefront of light passing through an optical system as compared to paraxial optical assumptions. Aberrations are mostly a result of the incompleteness of the paraxial optics theory but can also be a consequence of blemishes or dirtiness in optical elements. The theory of optical aberrations is well explored; the fundamentals are presented here. Additionally, a look at how these aberrations have influenced the arts, both historically and contemporarily, is put forth.

Typically, optical aberrations have acted to hinder the light-based arts. Aberrations are especially problematic in art forms that employ optical imaging systems. Very few artisans have embraced the aberrations as artistic tools; most dismiss them as unwanted and undesirable failures of the imaging system, and have striven to eliminate them. When seeking a perfectly sharp or clear photograph (e.g. the famously sharp nature images of Ansel Adams), an imaging system free of imperfections is ideal. However, in this pursuit, the simple and subtle beauty of the aberrational forms is discarded. In this work aberrations are elevated to be the photographic subject themselves. To capture the interferometric aberrational forms, a Michelson interferometer was constructed. Once the mirrors were aligned at near zero optical path length, the aligning helium-neon (HeNe) laser was removed and replaced with a tungsten-halogen white light source whose photons were delivered to the interferometer through a multi-strand fiber optic cable. Further adjustments of the mirrors were made using a diffraction grating to locate the white light interference fringes. Finally, the fringes were imaged onto color photographic film, developed, and printed using traditional color dark room techniques. Photographing the aberrational forms themselves invokes an interesting conversation, as the light fundamental to creating photographic artwork is itself now being photographed. Additionally, work that melds optical sciences and photography such as this is quite rare. Yet this combination of fields is exciting and noteworthy for it is in such blending that new opportunities for creativity abound. Moreover, those who push the norms in their fields are those who have the capacity to make world-changing discoveries.

Though much of this written work serves to educate and inform regarding the combination of art and optics, it is also serves as a formal presentation of the new body of artwork by the author titled *On the Bright Side*. *On the Bright Side* explores the tensions and beauty embodied in optical aberrations as detailed by the artist's statement. Accompanying the statement, each piece in the body of work is displayed. The interferometric point source shapes are rendered on large darkroom-based photographic prints; though scaled for size here, they are intended to present a visually compelling look at how optical data can exude a simple beauty of its own without needing interpretation.

Using the research done in this work as a springboard, a contemporary educational presentation is developed and tendered. Reaching students in developing years is critical to encourage and enlighten them to the possibilities their future could hold. STEM (Science, Technology, Engineering and Mathematics) outreach currently in progress informs youngsters of the possibilities within these fields. However, it often leaves out the multidimensional aspects of these disciplines, including the arts, and severely caps creativity. A modified approach to STEM outreach that weaves in the arts and creative thinking as well as illustrating nontraditional prospective vocations is presented. Even now, this new educational method called STEAM, which transforms research policy to put Art + Design (symbolized by the A in the acronym) at the center of STEM, encourages integration of Art + Design in K-20 education, and influences employers to hire artists and designers to drive innovation. This method is being adopted by institutions, corporations, and individuals worldwide.[2] Furthermore, designs for doing white-light interferometric photography experiments in elementary and high school classrooms have been developed and are introduced. Instructors or presenters can follow steps outlined in this research or in the modified experiments put forth. The equipment for this segment is specifically chosen to be easy to acquire and cost efficient. Troubleshooting is covered. Suggestions for implementation are given.

Concluding thoughts are presented as the entirety of this research is summarized. The importance of combining the fields of art and optics is reiterated. Special interest is given to how the artwork presented herein strives to reshape modern thinking regarding the two fields both individually and in their fruitful combinations.

1.1 A HISTORY OF ART AND OPTICS

1.1.1 Painting and Camera Obscura

Masters of the brush have long been known to capture the quintessence of this world - and that of myth, narratives, and imagination - with striking realism. From the earliest vestiges of human history, primitive artists chronicled their lives and stories through painting. As early as 36,000 years ago people, the first artists, used cave walls as a canvas to depict with a crude yet explanatory realism the events they experienced.[3] This simple form of recording human life continued to proliferate through culture where painting began to adorn man-made structures circa 6000 BC.[4] Throughout the many eons following, painting served a key role in adorning the sculptures and architecture of Ancient Egypt (3,000 ~ 30 BC), Greece (850 ~ 31 BC), and Rome

(500 BC – AD 476), as well as developing into an art form in its own right. The paintings of these three powerhouse civilizations though varying dramatically in style, purpose, and presentation all sought to portray reality. The Ancient Eastern civilizations of India, China, and Japan also established their proficiency utilizing painting to illustrate their cultures from 653 BC and into the modern era.

Though early studies in optics can be dated back almost as far as written documentation exists, it was during the height of Ancient Greek civilization that modern optical tradition commenced. Driven by ophthalmologic, astronomical, *and* artistic needs Greek philosophers and mathematicians studied vision. The mathematical tradition developed therein, championed by Euclid and Ptolemy, was concerned with "geometrical explanation and the perception of space" and was especially informative, applicable, and fulfilling to "the artist's concern for scenography".[5] As Greece fell, its optical traditions were integrated into the framework of Latin Christendom and Islam wherein the medieval science of optics was born.

Beginning in the early fourteenth century a renaissance of technological, scientific, theological, literary, and artistic pioneering transpired within the Western European cultures. It was during the Renaissance period that master painters such as Da Vinci and Caravaggio were perfecting their craft and providing the world with not only some of the most beautiful paintings ever produced, but some of the most uncannily accurate optically. While his priority never questioned but was suspected to be driven by the need to accurately portray visual phenomena, Renaissance founding father Filippo Brunelleschi developed linear perspective. From Brunelleschi to Galileo the major artists of the Renaissance and forward, "whatever their apparent diversities in theory and practice, shared for the most part one important underlying assumption, namely that the science of geometrical optics corresponded in a real way to the central facts of the visual process."[6] By using the geometric procedures of linear perspective these artisans were able represent three dimensional items on a flat surface such that it essentially represented the same visual arrangement as the eye would see.

The latter end of the Renaissance, known also as the Scientific Revolution, provided the backdrop to some of the most significant advancements in the field of optics as well. Partially driven by the Renaissance and post-Renaissance art culture's desire to "invent a machine or device for the 'perfect' imitation of nature," it was during this era that the camera obscura, previously conceived in the Middle Ages by optics scholar Alhazen (or Ibn al-Haitham) for studying the nature of light, was improved and employed in the arts.[7] In the mid 1500s a convex lens was added to the pinhole opening of the camera by Daniele Barbaro who used his more developed camera images to create accurate proportional diminution for artists.[8] Subsequently further improvements to increase the optical performance and correct the upside-down image were made. Johannes Kepler is credited with placing another lens in the system to re-invert the image in the seventeenth century, and also with the invention of the tented camera which could be transported. The "practical applications [of the tented camera obscura device] in topographical surveys – civil, military, and artistic – were readily apparent."[9]

Similar to the scientific community during this time, a painter's craft was founded upon empirical procedures, of which optical devices could directly aid. It would seem that on this basis the use of a camera obscura would become commonplace. However, when examining paintings of that era for the possible use of a camera obscura in their creation no entirely definite answer exists. Written evidence of artists who utilized a camera obscura in their works is almost entirely lacking and the visual evidence in the paintings themselves is subject to individual interpretation. Yet, beginning in the 1500s paintings began to reveal visual characteristics that believably point to the use of an optical aids. Fabric patterns with no ‘eyeballed’ awkwardness, highly realistic reflections in shiny metal, and perfect gradiation of light and shadows – an aesthetic now closely associated with photography – suddenly appeared in paintings toward the end of the Renaissance. The rapid jump in realism “was not a gradual process – the optical look arrived suddenly, and was immediately coherent and complete.”[10] Johannes Vermeer is probably the most notable painter who (more than likely) used optical instruments in his paintings. Much of the evidence to support this claim is found in his paintings themselves. “Vermeer seems to have been delighted by the optical effects of the lens and tried to re-create them on the canvas.”[11] He often would paint foregrounds out-of-focus as compared to a focused background and depict out-of-focus light with a ‘halo’ effect: these distortions cannot be seen with the naked eye! These optical artifacts can be seen in numerous Renaissance and post-Renaissance works, and are considered by many to be scientific evidence for the use of optics in paintings (see Hockney-Falco thesis).[12]

1.1.2 Photography and Cinematography

For centuries, artists closely followed the realism trend and while not all of them directly used optics, “most tried to emulate the naturalistic effects…of lens-based images.”[13] During this time, optically the camera obscura had become somewhat of a staple among artisans, but it was not until the early eighteenth century when chemical advancements would make it possible to ‘fix’ the images seen through it. The earliest existing photographic process was created circa 1816 by Joseph Nicéphore Niépce who used a camera mechanism, biconvex lens, a diaphragm, and paper sensitized with silver chloride. His process created negatives of scenes it recorded, and was discarded at the time for processes that produced positive images. In 1829, Niépce and famous optical entertainer Louis Daguerre agreed to collaborate. Armed with Niépce’s research, Daguerre perfected a process in 1839 that fixed lifelike images on highly polished silver plates. These Daguerreotypes instantly created a mania, especially with the educated and upper-class society and their growing demand for realistic art. Daguerre himself promoted the daguerreotype process and results, even arranging for the manufacture of lenses and wooden cameras. Around the same time in England, scholar and scientist William Henry Fox Talbot who was frustrated with his inability to draw well saw the promise of optical systems to create lifelike images and independently created an imaging process using camera optics and the light-sensitive chemistry of silver salts. His process also created negatives, but through experimentation he was able to solve this problem by "taking the negative image and reprinting it in direct contact with an unexposed, treated piece of paper, establishing a nascent negative/positive photographic method."[14] Contributing the final piece to the puzzle, astronomer John Herschel shared his discovery that hyposulfite of soda would dissolve silver salts and thereby make images permanent with both Daguerre and Talbot. Herschel never considered himself an artist but his contributions shaped and founded the concepts of the photographic process. He is also credited with establishing a common nomenclature by consistently referring to the broad terms of 'photography' (derived from two Greek words meaning light and drawing) and 'to photograph.'

Over the subsequent nearly two centuries photography grew from its humble beginnings to the illustrious art form it is known as today. Art and optics are nowhere as closely intertwined as within the history of photography. With the common goal of recording as truthfully as possible and permanently affixing subjects on photographic media, wet-plate, tin-type, carte de visite, and many other forms of photo chemistry were developed based on Talbot's original processes and proliferated throughout the culture. As events transpired and advances made cameras and processing darkrooms more portable, photography became a tool of news reporters and propagandists, especially during the American Civil War. However, while the chemical methodology and portability of photography made significant advances in the later 1800s, the foundational optical system employed in photography stayed mostly the same. Yet the action of warfare and events considered newsworthy of the time pushed photographic optics to become faster. In 1878 Eadweard Muybridge used a series of cameras with shutters on tripwires to photograph a galloping horse. Viewed individually, the images from each camera provided photographic proof for scientific theories at the time. Viewed in succession through a zoetrope or similar device the images made a short “movie” – a photographic first. In the following years celluloid film and personal cameras were introduced, taking artistic realism from only a handful elite artisans and putting it in the hands of everyone.

With photographic imagery so readily accessible, it came as no surprise that only about 15 years after Muybridge’s original ‘movie’ and preceded by several motion picture viewing devices the cinématographe was invented. This device was a motion picture camera capable of also projecting and printing, but used the same base optics as the then standard still photographic cameras. The early 1900s saw the motion picture explode through culture and brought with it a heightened sense of realism. Throughout the ensuing half century both cinematography and photography were on the cutting edge of development. These advances, such as color film, telephotography, strobe lighting, and holography, allowed lens based artists to record and reproduce the events they saw with a previously unimagined level of authenticity. Yet despite these larger technological advances in the photographic and cinematographic fields, the fundamental optics principles and tools upon which these two art forms operated remained remarkably similar to their century’s prior precursor. Now even in the generation of computer aided photography/cinematography where the 'truth' of an image is often blurry, the optics employed are the same, albeit improved and perfected to a significantly greater degree.

1.1.3 Optics in Other Various Art Genres

The most obvious connection between the arts and optical sciences is through photography. However, the influence of optics can be seen across multiple disciplines of art throughout history. Renaissance and pre-renaissance phantasmagoria shows and dioramas used lenses and lighting, optical illusions, and the camera obscura long before its use for photography "in the context of natural magic, as a means of exploiting natural phenomena to astonish and entertain the spectator."[15] These optical techniques and practices of old, to direct the viewers' attention through an experience, have carried over into modern theater where spotlights now have back collection reflectors and shutters and fill lights have array lenses, interchangeable color gels or LED light arrays, and/or bokeh shaping filters. Beyond providing illumination for the theater, actors and especially dancers, can now even interact with light through optics and digital media as they perform on stage.[16] In the same way optical illusions used to awe audiences, optical feats are still used in modern shows of widely varying natures. One of the most notable of these optical devices is the laser. Anything from music concerts to sporting events to nighttime theme park shows to simple fountains and conferences can showcase laser light shows create a stunning pop color or even images to captivate audiences.

Optics also has a place in arts beyond the stage and performance aspects. Architects now use strategically placed lighting to highlight stunning aspects of their work and create a heightened sense drama for a seemingly ordinary subject. In sculpture, artists have used polarization and dichroics to achieve stunning effects in glass and instillation works.[17,18] Simple optical color theory and polarization effects have also been used in stained glass windows in churches, cathedrals, and buildings worldwide for hundreds of years. On the preservation side of art, conservators have been using non-contact optical imaging techniques (often involving lasers and infrared reflectivity) to "study intricate details, analyze pigments, and search for subtle defects not visible to the naked eye" in the art restoration process.[19] So while the obvious connection between art and optics is found still in photography, it is clear that optical sciences plays a large part in countless other art genres.

CHAPTER 2 – Optical Aberrations in Art

2.1 A BRIEF INTRODUCTION TO OPTICAL ABERRATIONS

An optical aberration is defined as any departure of an optical system from the paraxial optics predictions. In paraxial optics, light travels from the source point and is imaged to a distinct point in the image. However, it is seen in reality that "a wide beam of rays incident on a lens parallel to the axis, for example, is not brought to a focus at a unique point."[20] There are two main types of aberrations – chromatic and monochromatic. Chromatic aberrations arise "from the fact that *n* [index of refraction of a medium] is actually a function of frequency or color."[21] This research primarily focuses on the latter type of aberrations, monochromatic. Monochromatic aberrations can be further categorized into two subgroupings: those that deteriorate the image (such as spherical aberration, coma, and astigmatism) and those that deform the image (such as field curvature and distortion). Of these two subgroupings, this research primarily employed the aberrations that deteriorate the image. As such, the predominant focus of this introduction will be on the image-deteriorating monochromatic aberrations and assumes a basic understanding of paraxial optics.

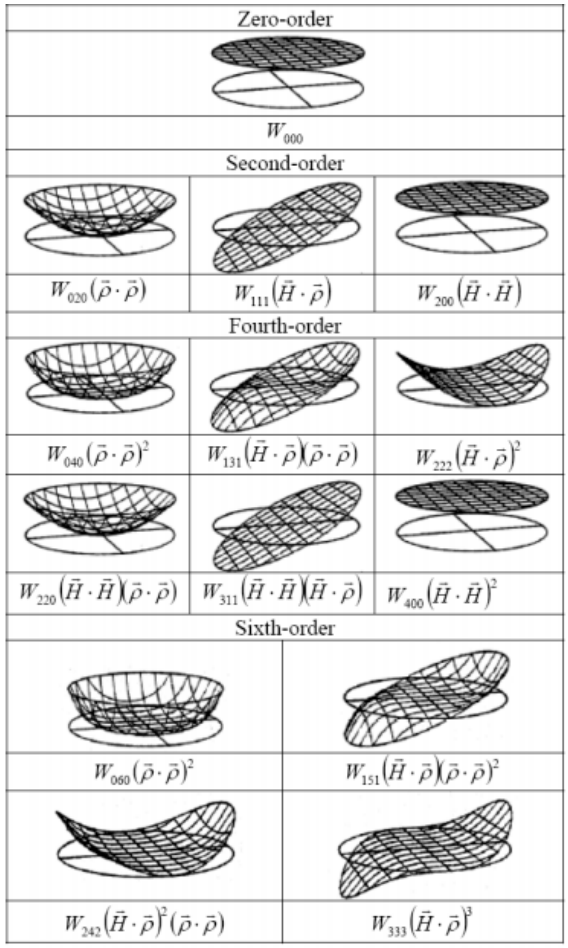


Figure 1 - Basic wavefront deformation shapes. All of the basic deformations are either axially symmetric, double plane symmetric, or plane symmetric. [22]

2.1.1 Wavefront Equation

The most basic approach to understanding aberrations is by observing a system according to its symmetry and thereby simplifying theoretical treatments through physical observations. When real images are not sharp for example, it can be concluded that the wavefront has been deformed from a spherical shape. Likewise, assuming the wavefront deterioration is smooth, the nature of the wavefront can be analyzed through symmetry and “may have axial symmetry, double plane symmetry, or plane symmetry.”[23] The basic forms of symmetry and how they apply to a wavefront surface are illustrated in Figure 1.

$$W(\vec{H},\ \vec{\rho}) = \sum_{j,m,n} W_{k,l,m}(\vec{H}\cdot\vec{H})^{j}(\vec{H}\cdot\vec{\rho})^{m}(\vec{\rho}\cdot\vec{\rho})^{n} \tag{2.1}$$

Examining the wavefront deformation mathematically, the aberration function (Eq. 2.1) describes the surface "at the exit pupil as a function of the normalized field $\vec{H}$ and aperture $\vec{\rho}$ vectors."[24] Within the aberration function, $W_{k,l,m}$ represents the aberration coefficients and the sub-indices *j, m,* and *n* are integers $k = 2j + m$, $l = 2n + m$. As the aberration function is scalar, it involves the dot products of the field and aperture vectors to describe axial symmetry. These dot products are only dependent on the magnitude of the field and aperture vectors and the cosine of the angle (ϕ) between them. The wavefont deformation is provided by the aberration function in terms of optical path length along the ray defined by the tip of the field vector and the tip in terms of optical path length along the ray defined by the tip of the field vector and the tip of the aperture vector and the distance between the actual wavefront and the reference sphere. Written to sixth order approximation, the aberration function is as follows in Eq. 2.2. Each term of the approximation is representative of a single aberration (coma, astigmatism, etc.) as a way the

$$\begin{aligned}
&W(\vec{H},\vec{\rho}) \\
&= W_{000} + W_{200}(\vec{H}\cdot\vec{H}) + W_{111}(\vec{H}\cdot\vec{\rho}) + W_{020}(\vec{\rho}\cdot\vec{\rho}) + W_{040}(\vec{\rho}\cdot\vec{\rho})^2 \\
&+ W_{131}(\vec{H}\cdot\vec{\rho})(\vec{p}\cdot\vec{p}) + W_{222}(\vec{H}\cdot\vec{\rho})^2 + W_{220}(\vec{H}\cdot\vec{H})(\vec{\rho}\cdot\vec{\rho}) + W_{311}(\vec{H}\cdot\vec{H})(\vec{H}\cdot\vec{\rho}) \\
&+ W_{400}(\vec{H}\cdot\vec{H})^2 + W_{240}(\vec{H}\cdot\vec{H})(\vec{\rho}\cdot\vec{\rho})^2 + W_{331}(\vec{H}\cdot\vec{H})(\vec{H}\cdot\vec{\rho})(\vec{\rho}\cdot\vec{\rho}) \\
&+ W_{422}(\vec{H}\cdot\vec{H})(\vec{H}\cdot\vec{\rho})^2 + W_{420}(\vec{H}\cdot\vec{H})^2(\vec{\rho}\cdot\vec{\rho}) + W_{511}(\vec{H}\cdot\vec{H})^2(\vec{H}\cdot\vec{\rho}) + W_{600}(\vec{H}\cdot\vec{H})^3 \\
&+ W_{060}(\vec{\rho}\cdot\vec{\rho})^3 + W_{151}(\vec{H}\cdot\vec{\rho})(\vec{H}\cdot\vec{H})^2 + W_{242}(\vec{H}\cdot\vec{\rho})^2(\vec{\rho}\cdot\vec{\rho}) + W_{333}(\vec{H}\cdot\vec{\rho})^3
\end{aligned} \tag{2.2}$$

Table 2.1 - Wavefront aberrations and their corresponding vector and algebraic forms as well as the sub-indices j, m, and n from the aberration function.

Aberration Name	Vector Form	Algebraic Form	*j*	*m*	*n*
Zero Order					
Uniform Piston	W_{000}	W_{000}	0	0	0
Second Order					
Quadratic Piston	$W_{200}(\vec{H}\cdot\vec{H})$	$W_{200}H^2$	1	0	0
Magnification	$W_{111}(\vec{H}\cdot\vec{\rho})$	$W_{111}H\rho\cos\phi$	0	1	0
Focus	$W_{020}(\vec{\rho}\cdot\vec{\rho})$	$W_{020}\rho^2$	0	0	1
Fourth Order					
Spherical Aberration	$W_{040}(\vec{\rho}\cdot\vec{\rho})^2$	$W_{040}\rho^4$	0	0	2
Coma	$W_{131}(\vec{H}\cdot\vec{\rho})(\vec{\rho}\cdot\vec{\rho})$	$W_{131}H\rho^3\cos\phi$	0	1	1
Astigmatism	$W_{222}(\vec{H}\cdot\vec{\rho})^2$	$W_{222}H^2\rho^2(\cos\phi)^2$	0	2	0
Field Curvature	$W_{220}(\vec{H}\cdot\vec{H})(\vec{\rho}\cdot\vec{\rho})$	$W_{220}H^2\rho^2$	1	0	1
Distortion	$W_{311}(\vec{H}\cdot\vec{H})(\vec{H}\cdot\vec{\rho})$	$W_{311}H^3\rho\cos\phi$	1	1	0
Quartic Piston	$W_{400}(\vec{H}\cdot\vec{H})^2$	$W_{400}H^4$	2	0	0
Sixth Order					
Oblique Spherical Aberration	$W_{240}(\vec{H}\cdot\vec{H})(\vec{\rho}\cdot\vec{\rho})^2$	$W_{240}H^2\rho^4$	1	0	2
Coma	$W_{331}(\vec{H}\cdot\vec{H})(\vec{H}\cdot\vec{\rho})(\vec{\rho}\cdot\vec{\rho})$	$W_{331}H^3\rho^3\cos\phi$	1	1	1
Astigmatism	$W_{422}(\vec{H}\cdot\vec{H})(\vec{H}\cdot\vec{\rho})^2$	$W_{422}H^4\rho^2(\cos\phi)^2$	1	2	0
Field Curvature	$W_{420}(\vec{H}\cdot\vec{H})^2(\vec{\rho}\cdot\vec{\rho})$	$W_{420}H^4\rho^2$	2	0	1
Distortion	$W_{511}(\vec{H}\cdot\vec{H})^2(\vec{H}\cdot\vec{\rho})$	$W_{511}H^5\rho\cos\phi$	2	1	0
Piston	$W_{600}(\vec{H}\cdot\vec{H})^3$	$W_{600}H^6$	3	0	0
Spherical Aberration	$W_{060}(\vec{\rho}\cdot\vec{\rho})^3$	$W_{060}\rho^6$	0	0	3
Un-Named	$W_{151}(\vec{H}\cdot\vec{\rho})(\vec{H}\cdot\vec{H})^2$	$W_{151}H\rho^5\cos\phi$	0	1	2
Un-Named	$W_{242}(\vec{H}\cdot\vec{\rho})^2(\vec{\rho}\cdot\vec{\rho})$	$W_{242}H^2\rho^4(\cos\phi)^2$	0	2	1
Un-Named	$W_{333}(\vec{H}\cdot\vec{\rho})^3$	$W_{333}H^3\rho^3(\cos\phi)^3$	0	3	0

wavefront can be deformed with respect to the reference sphere. Combined, these terms produce the actual wavefront deformation *W* in light of the multiple aberrations that could be present. Table 2.1 further details the given name associated with each aberration, as well as the vector and algebraic form of the aberration term in the aberration function and the sub-indices for each term.

Often, the fourth order terms are referred to as the primary aberrations. In this research these were the aberrations that were most often induced into the system to achieve the desired results. While minute changes were possible, for the most part the zero order and second order aberrations did not produce significantly noticeable and aesthetic changes to the interferogram that warranted imaging for this research.

2.1.2 Zernike Polynomials

While the aberration function as explored above and introduced by optics pioneer Rowland V. Shack is an elegant study, several examinations of the aberrations exist. The software to operate the deformable mirror employed in this research functions by using the base system of Zernike polynomials for all deformations. These polynomials represent basic wavefront deformation shapes seen in optics and, similar to the aberration function, the terms can be combined to give a more complete picture of the actual wavefront shape. The Zernike polynomials are limited; while they are a complete set, some wavefront errors simply cannot be represented using a reasonable number of Zernike polynomial terms. In the research the number and shape of the aberrations that could be created were limited to those following the allotted Zernike polynomials programed in the deformable mirror software.

Named after mathematician Frits Zernike, the Zernike polynomials are a sequence of orthogonal polynomials in two real variables, ρ and ϕ (radial polynomial and azimuthal frequency respectively), with several unique mathematical properties. Firstly, the Zernike polynomials have simple rotational symmetry; rotating the coordinate system does not change the form of the polynomial.[25] The radial function, R, "must be a polynomial in ρ of degree n and contain no power of ρ less than m."[26] There are even and odd Zernike polynomials which are defined respectively as follows in Eqs. 2.3 and 2.4. If m is even, $R(\rho)$ must also be even. Similarly, if m is odd, $R(\rho)$ will be odd.

$$Z_n^m(\rho, \phi) = R_n^m(\rho)\cos(m\phi) \tag{2.3}$$

$$Z_n^{-m}(\rho, \phi) = R_n^m(\rho)\sin(m\phi) \tag{2.4}$$

The radial polynomial is often tabulated as $R_n^m(\rho)$ as a special case derivative of Jacobi polynomials with a normalization property of

$$R_n^m(1) = 1 \tag{2.5}$$

and orthogonality property given by

$$\int_0^1 R_n^m(\rho)R_{n'}^m(\rho)\,\rho d\rho = \frac{1}{2(n+1)}\delta_{nn'} \tag{2.6}$$

In practice "it is convenient to factor the radial polynomial into

$$R_{2n-m}^m(\rho) = Q_n^m(\rho)\rho \tag{2.7}$$

where $Q_n^m(\rho)$ is a polynomial of the order 2(*n*-*m*). $Q_n^m(\rho)$ can be written generally as"[27]

$$Q_n^m(\rho) = \sum_{s=0}^{n-m}(-1)^s\frac{(2n-m-s)!}{s!\,(n-s)!\,(n-m-s)!}\rho^{2(n-m-s)} \tag{2.8}$$

Applying this information to the wavefront deformation, the complex exponentials are usually written as sines and cosines and usually expressed as follows in Eq 2.6 where A_n, B_{nm}, and C_{nm} are individual coefficients and $\overline{\Delta W}$ is the mean wavefront deformation.

$$W = \overline{\Delta W} + \sum_{n=1}^{\infty}\left[A_n Q_n^0(\rho) + \sum_{m=1}^{n} Q_n^m(\rho)\rho'(B_{nm}\cos m\phi + C_{nm}\sin m\phi')\right] \quad (2.6)$$

At least six different numbering schemes exist for the Zernike polynomials. The one utilized by the deformable mirror employed in this research was different than what appears in most literature. Since the numbering scheme of the deformable mirror was so distinct, the first 26 Zernike polynomials along with the aberration associated with it are presented in Table 2.2 according to more recognizable literature standards.

2.2 ABERRATIONS PRESENT IN ART

While far from common, aberrations and the use of aberrations in art is not a completely new occurrence. Clues that disclose the use of optics, as well as their inherent aberrations, throughout art history have been discovered. A select few artists have gone further to specifically isolate the aberrations or, more commonly, aberration effects in their work.

2.2.1 Historical

One of the most prominent aberration-type effects to be used beginning in early Renaissance art was anamorphosis. Anamorphoses present "a distorted image that appears in natural form under certain conditions, as when viewed at a raking angle [perspective or oblique anamorphosis] or reflected from a curved mirror [mirror or catoptric anamorphosis]."[28] Hans Holbein the Younger's 1533 painting *The Ambassadors* is one of the most cited examples of oblique anamorphosis. When viewed from a sharp angle the distorted image across the bottom of the painting transforms into the image of a skull.[29] This and many other Renaissance era paintings dabbled in the effects of specific vantage point and reflection and, though their creators most likely

Table 2.2 - First 26 Zernike polynomials and their associated aberration names.

$Z_{\#}$	Polynomial	Aberration
0	1	Piston
1	$\rho\cos\phi$	Tilt x
2	$\rho\sin\phi$	Tilt y
3	$2\rho^2 - 1$	Defocus
4	$\rho^2\cos 2\phi$	Astigmatism x
5	$\rho^2\sin 2\phi$	Astigmatism y
6	$(3\rho^2 - 2)\rho\cos\phi$	Coma x
7	$(3\rho^2 - 2)\rho\sin\phi$	Coma y
8	$6\rho^4 - 6\rho^2 + 1$	Primary Spherical Aberration
9	$\rho^3\cos 3\phi$	Trefoil x
10	$\rho^3\sin 3\phi$	Trefoil y
11	$(4\rho^2 - 3)\rho^2\cos 2\phi$	Secondary Astigmatism x
12	$(4\rho^2 - 3)\rho^2\sin 2\phi$	Secondary Astigmatism y
13	$(10\rho^4 - 12\rho^2 + 3)\rho\cos\phi$	Secondary Coma x
14	$(10\rho^4 - 12\rho^2 + 3)\rho\sin\phi$	Secondary Coma y
15	$20\rho^6 - 30\rho^4 + 12\rho^2 - 1$	Secondary Spherical
16	$\rho^4\cos 4\phi$	Tetrafoil x
17	$\rho^4\sin 4\phi$	Tetrafoil y
18	$(5\rho^2 - 4)\rho^3\cos 3\phi$	Secondary Trefoil x
19	$(5\rho^2 - 4)\rho^3\sin 3\phi$	Secondary Trefoil y
20	$(15\rho^4 - 20\rho^2 + 6)\rho^2\cos 2\phi$	Tertiary Astigmatism x
21	$(15\rho^4 - 20\rho^2 + 6)\rho^2\sin 2\phi$	Tertiary Astigmatism y
22	$(35\rho^6 - 60\rho^4 + 30\rho^2 - 4)\rho\cos\phi$	Tertiary Coma x
23	$(35\rho^6 - 60\rho^4 + 30\rho^2 - 4)\rho\sin\phi$	Tertiary Coma y
24	$70\rho^8 - 140\rho^6 + 90\rho^4 - 20\rho^2 + 1$	Tertiary Spherical

25	$\rho^5 \cos 5\phi$	Pentafoil x
26	$\rho^5 \sin 5\phi$	Pentafoil y

used optical devices in their production, they are more optical illusions than lens based optical aberrations.

As presented previously, based on specific optical effects present in Renaissance era art it is highly likely that lenses and/or mirrors were used to help artists perfect the realism in their craft. Yet painters like Vermeer, who delighted in optical effects and the ‘photographic’ look, showcase a few small optical aberration effects. It is often argued that circles of confusion from a defocused portion of the image were often painted in his works and some perspective abnormalities can be explained with spherical and other aberrations.[30] With authenticity still the goal, highly aberrated images from this time as a result of flawed optics are simply not found. In fact, differing focal points and magnifications throughout many Renaissance paintings, especially near the edge of the image, are clues that artisans had the knowledge of image degrading optical aberrations and refocused the image instead of painting them.[31]

2.2.2 Contemporary

In the years leading up to the and even after the invention of photography, art followed a distinctly realistic trend. However, as photography became available to the masses, painters sought to differentiate themselves from the new prevalent pictorial ‘truth’ by diverging for the first time in known history from realism. The Impressionist movement of the late 1800s opened the door to modern art, but also seems to have closed the door to optically aided painting. During the following century, modern art (in the genre of painting) veered further and further from realism while concurrently photography and cinematography produced the most highly realistic images ever known. The quest for realism was in a sense passed on to photographers and cinematographers and lens-based images became a standard for truth.[32] As such, optical aberrations, aberration effects, or anything that would detract from an image's truthfulness became even less common.

It is only with the advent of computer aided artistry (circa 1970s) where the lines between truth and that which was created have become blurred. While photography and cinematography no longer hold the special, even legal, position of truth they once did, this new era relative truth in art (and culture) has freed artists to explore optical aberration effects in their work more than ever before. Yet, to date and current knowledge, this subject and application in art remains widely unexplored.

CHAPTER 3 – Aberrations as the Photographic Subject

3.1 MOTIVATION

In much of traditional photographic processes the artwork strives to portray a near replica of reality as it is seen. Obviously, as all art forms have been, practitioners have manipulated the captured image to challenge standards and create unique works. Ansel Adams, who deliberately modified images and exposures to create artistic effects, is a notable example. His straightforward 'Zone System' for achieving specific darkroom printing results is the basis for many of the capabilities of modern photo editing software. However, usually within fine art photography, this augmentation to produce the artist's desired product is typically never within or from the lens itself. Photographers of old would manually doge and burn their darkroom prints to their liking or double expose film in camera; modern photographers overlay gradients, change colors, or digitally enhance (to name a few) their images in computer based editing programs. What photographers throughout the ages have shared regardless of how they ultimately produce their images is that their lenses when used (correctly) in a simple application would give an accurate image of the object being photographed. For so long photographic artists as well as proponents of optical sciences like astronomy, biomedical imaging etc. have strived to make their optical systems as aberration free as possible. Regardless of what is done with or to the image after it is recorded, most agree that a sharp image is desirable. Even the Latin and Hebrew bases for the word aberration indicate that this ‘wandering’ or ‘erring’ has had a strongly negative connotation for centuries. However, in this striving to eradicate aberrations from optical systems in search of the sharpest image, the simple beauties of the aberrational forms have been discarded. Instead of a passing mention in the quest for the most optically perfect (sharp/aberration free) system, here aberrations – which are just as ‘real’ as what is seen – are elevated to become the sought after and the desirable result. The bigger the deformity, the more interesting the final resulting photographic image is. Furthermore, most photographers utilize light; light illuminates the object, light enters the camera system to record an image, and by light an image is produced or displayed. Here light is elevated from tool to photographic subject using interferometric techniques. Thus in this study and ultimately the resulting body of photographic work, both light and aberrations, two things normally undesired or even taken for granted, are the motivation, focal point, and subject.

3.2 A BRIEF HISTORY ON INTERFEROMETRY

The word interferometry is a derived form of the word interferometer, a hybrid itself from interfere and meter, defined as an “instrument for measuring the interference of light.”[33] It follows that interferometry in its broadest sense is the study of light’s interference and the family of techniques utilized to superimpose wave fronts with different phases and extract information from the resulting pattern. While many instruments can successfully overlay light so the waves interfere, a Michelson interferometer was used in this research for its simplicity, accessibility for component interchange necessities, and historical successes with white-light sources.

3.2.1 Michelson Interferometry

The Michelson interferometer was developed by Albert. A Michelson in the late 19th century for use in speed of light measurement experiments among other applications and became famous for its critical role in the Michelson-Morley Experiment (which ultimately disproved the existence of a stationary aether substance necessary for light propagation).[34] Though its applications have become numerous in the ensuing years, the main optical components of a Michelson interferometer still simply consist of two highly polished plane mirrors and two plane-parallel glass plates[i] (one with a half-silvered coating). The half-silvered mirror sends beams from an extended source "in quite opposite directions against [the] plane mirrors, whence they are brought together again to form interference fringes" by combining one beam with a time-delayed version of itself.[35] One common Michelson interferometer arrangement is shown schematically in Figure 2, where the half-silvered surface is designated by a darker edge on the beam splitter. Ray paths are denoted along with their directionality to illustrate the behavior of the light as it moves through the instrument. Depending on the experiment, the optical path between the beam splitter and the respective mirrors may be the same or slightly different. Many applications utilize an imaging lens to enlarge the interference results, however just the naked eye, viewing screen, piece of photographic film, CCD sensor, or camera device may be used to analyze the interference results obtained.

---

[i] The beam splitter and, if used, the compensator plate in a Michelson interferometer are made out of glass or fused silica for work in the near ultraviolet, visible, and near infrared, potassium bromide for the mid infrared, and polystyrene for the far infrared.

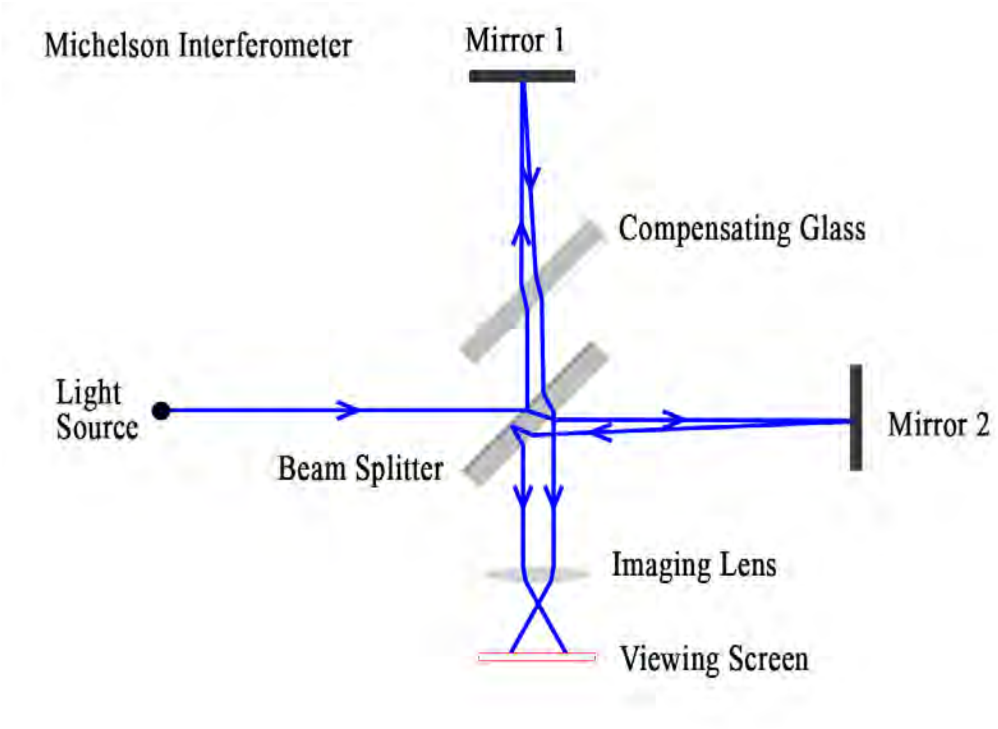


Figure 2 -Michelson interferometer diagram with ray paths created by author.

For successful experimental results with a Michelson interferometer several requirements must be met. Firstly, to be considered a Michelson type interferometer, light entering the interferometer must originate from an extended source. If the source is not sufficiently large, the light must pass through a collimating assembly or a ground glass (or similar) screen near the source to give the appearance that it originates from an extended point to completely fill the mirrors. Coherence, or a point-to-point correspondence of the phase between the two sources so the resulting interference pattern remains steady, is absolutely essential. Traditional Michelson interferometry used monochromatic sources such as sodium or mercury lamps to obtain coherent light more easily. Modern lasers which produce coherent light are commonly used with great ease in contemporary applications. While monochromatic and laser sources do add simplicity to experimentation, it is possible to use a multi-wavelength or white light source as well. The distance over which the light is coherent is significantly smaller in applications using the aforementioned sources and as such the optical systems must be compact. Thus a coherent, extended source is required for Michelson interferometry.

Additionally, for the Michelson interferometer to produce viewable results certain mechanical stipulations must be met. At least one of the mirrors in the interferometer must be able to move along the optical path in both course and fine adjustment increments. The beam splitter must be half-silvered to allow some of the light to pass through and some to be reflected; a 50%-50% ratio of reflected to transmitted light is ideal. The interferometer system must operate on a vibration-free surface. Even minute mechanical vibrations can disrupt the coherence of the source making interference impossible. In order to generate an interference pattern from a Michelson interferometer, at least one mirror must be movable, the beam splitter must be able to send light in two directions via a half-silvered coating, and the whole interferometer system must be on a mechanically stable base, such as an optical table.

Modern applications which make use of Michelson interferometry are quite extensive. Most notably, Michelson interferometers are utilized often for atmospheric and astronomical applications. Many of the world's leading astronomical telescopes such as the Mt. Wilson Observatory's CHARA array include Michelson interferometers in their analysis systems to measure "diameters, distances, masses, and luminosities of stars" in high resolution among other contemporary astronomy applications.[36] Furthermore, almost all almost all modern infrared spectrophotometers are based upon Michelson interferometers that generate interferograms. The interferograms are subsequently converted into infrared spectra by fast Fourier transformation (FFT) to identify a substance of any state under test. Michelson interferometric systems are also widely used in optical testing practices.[37]

3.2.2 White-Light Interferometry

Before the advent of the laser in the 1960s, interferometry was conducted almost solely with monochromatic (atomic emission lamps) or white light. Monochromatic sources, such as a sodium lamp, allow for coherence to be achieved somewhat easily making experimentation and testing more straightforward. As long as the optical paths of Michelson instrument arms are small and equal enough, coherence and thereby interference is attainable with a while-light source. The optical path difference between the two arms must be as close to zero as possible since coherence across the multiple wavelengths inherent to white-light will only occur when this condition is met. These specific path length requirements necessary for white-light interference do produce high contrast fringes which constitute a powerful measurement tool.[38]

Though many white-light sources are currently available, all have varying color temperatures. In many applications the color temperature of the white-light source does not present a significant concern. The interference process effectively separates the light's compositional colors allowing for the data to be unmarred by the source's original color cast.

As previously discussed, a Michelson interferometer's source must be extended regardless of the source type. With a white-light source several conditions must be considered. Many white-light sources are filament style incandescent light bulbs, the light of which must be passed through a diffusing glass not only to meet extended source requirements but also so the filament is not imaged through the system. Furthermore, the white-light source must be directed into the system. A regular, unassisted light bulb will not provide enough light through the system to produce visible interference; additionally, much of the source light will be lost out the back of the system if not collected in some manner. Simple reflectors or fiber optic cables are effective ways to guide the largest amount of light from the source through the system. A silica fiber optic cable is ideal for

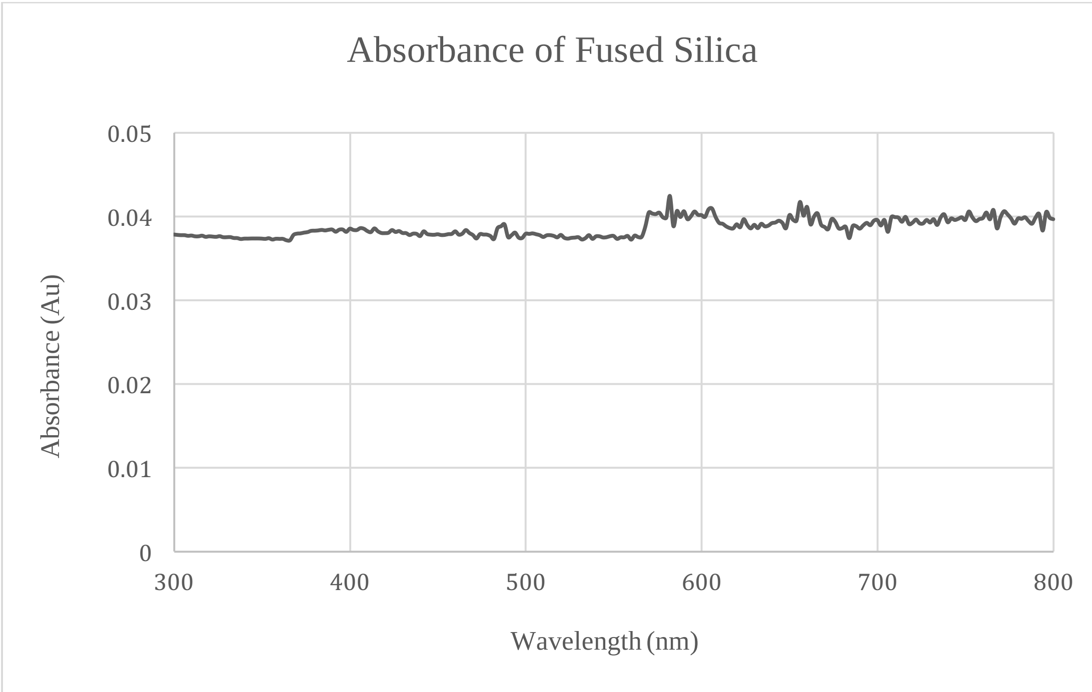


Figure 3 - Fused silica absorption spectrum from the ultraviolet to the near infrared wavelengths. The visible spectral region extends from approximately 400-700 nm. This spectrum was measured on an OLIS/Hewlett-Packard 8452A diode array spectrophotometer against an air reference.

white light interferometry since silica transmits well throughout the visible spectrum (see Figure 3).

To obtain white-light fringes with a Michelson interferometer the path lengths of the two arms of the interferometer must be matched to within a few μm. This level of accuracy requires the movable test mirror of the interferometer to have both fine and coarse adjustability. A differential position micrometer, affording both coarse and fine adjustments of the moveable mirror assembly, is a simple solution which was utilized in this situation. Changes in optical pathlength induced by the differential micrometer could be monitored by a precision dial indicator. Even with such fine adjustment, finding the elusive white-light interference fringes can be a challenge. Many techniques for locating the white-light fringes exist, and “most of these employ a monochromatic light source to locate approximately the zero path difference condition and then a *very* slow motion of the interferometer mirror to bring the white light fringes into view."[39] This process can be very tedious, requires extreme precision, and the starting point for fringe location is not certain. By using a fairly coarse (1000 lines/mm) transmission grating, the procedure detailed by Bell and Tubbs was used in this research. The white light fringes can be located in the spectrum outside the field of the interferometer. The fringes can then be brought into view "making the final adjustment for zero path difference a relatively simple and rapid process."[40]

For white light interferometry, the optical path lengths will vary depending on the light's wavelength. This miniscule difference will cause the various component wavelengths of the white light to go through the system at slightly different angles and image at slightly different positions giving rise to separation of color in the repeated multi-color patterns. An example of this separation of colors (wavelengths) from the first order fringe and the production of straight, white-light interference fringes created by the author for this research is shown in Figure 4. These patterns can also be correlated with the optical path difference in the two legs of the Michelson interferometer as shown in Figure 5.

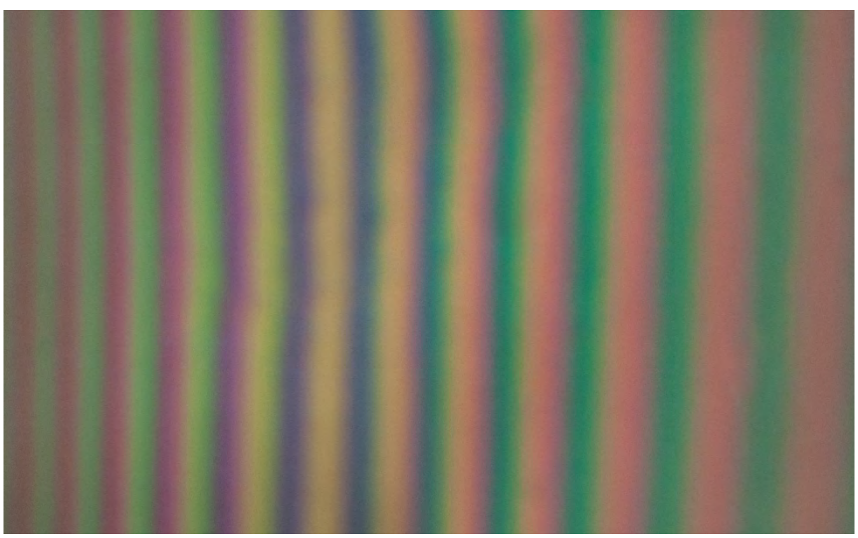


Figure 4 – Digital image of the color separation in a near straight-line, white-light interference fringes imaged for this research. The first order fringe (the darkest color fringe, here what appears to be navy blue) can be seen near the middle of the image. Resolution is sharpest near the first order fringe and falls off to each side. Differing dispersion causes a slight variation in colors on each side of the first order fringe.

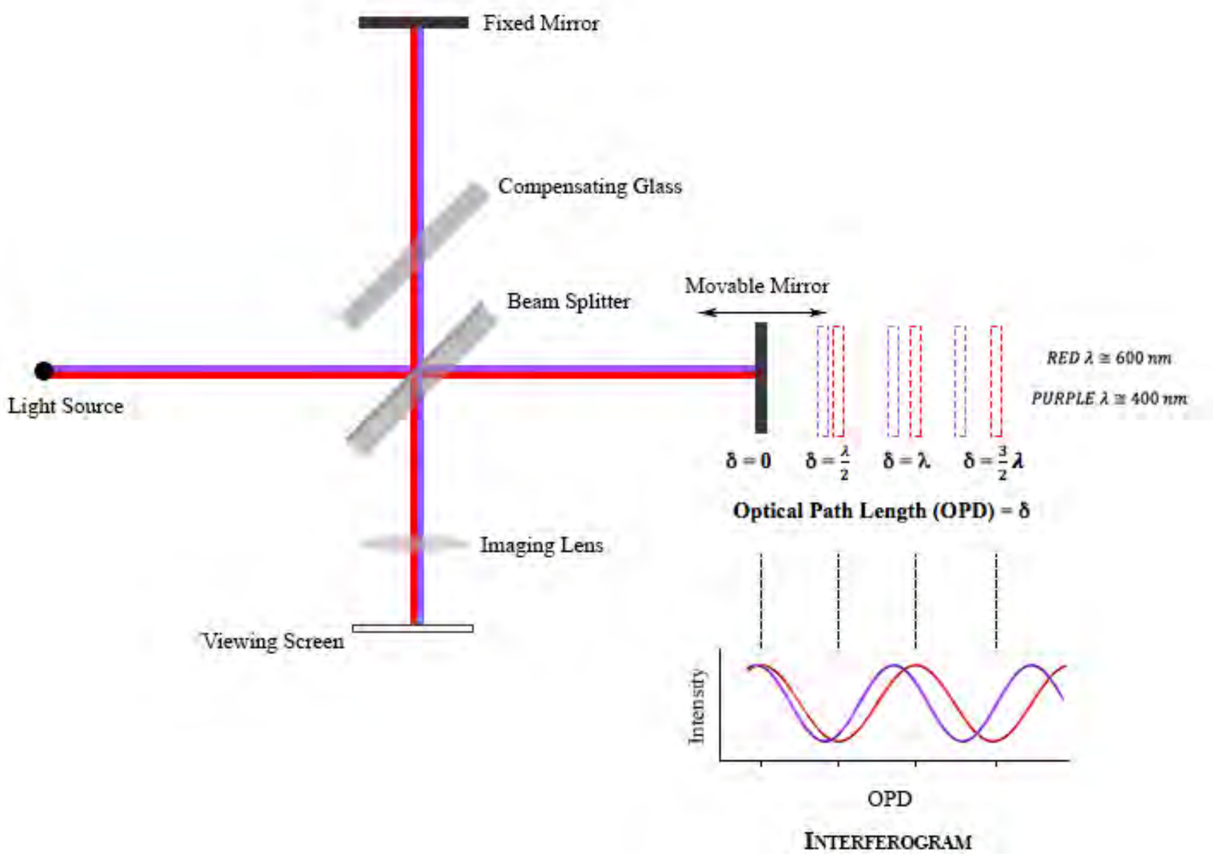


Figure 5 - Optical path difference between two different visible wavelengths (red, purple) and the resulting positions on an interferogram. Figure created by author.

3.2.3 Image Capture and Printing

From the inception of interferometry, the need to record the resulting interferogram for analysis has always been a necessity. Photography, or light writing/drawing from the original Greek (fotographía-φωτογραφια), has served as the primary recording tool for interferometry throughout the generations. With technological advances most modern interferometric systems record results directly to a computer via a CCD (charge-coupled device) detector. This light sensitive integrated circuit records data much in the same way that film and glass photographic plates did prior to its invention. While CCD detectors make contemporary analysis more efficient and eliminate chemical hazards associated with darkroom photography, the CCD is inherently limited to the resolution of the pixels within. Darkroom film and photographic paper record data by exposing silver nitrate (in black and white photography) molecules to light; similar light sensitive chemicals are utilized for color darkroom photography. Thus the level of detail, shading, and resolution in darkroom documentation is higher than modern technology has achieved at this point as the resolution is only limited by the size of the light sensitive molecule. For the preservation of highly detailed results as well as the obvious links to fine art photography for which this research was groomed, the more elementary method of darkroom photographic processes was chosen as the recording method here.

3.3 EXPERIMENTAL

For this research a Michelson interferometer was constructed from scratch, first on an aluminum optical breadboard and then on a heavy, vibrationally-damped optical table using standard modular optics components from Newport and Thorlabs as well as some custom-fabricated components. Once completed the instrument was tuned to work with a white light source. Special equipment was created to record the resulting data interferograms onto medium-format (4” × 5”) photographic film (Kodak Ektar 100 ISO). After taking as many images of the data as the system allowed, one of the plane mirrors was replaced with a deformable mirror. Using the accompanying software, numerous aberrational forms were created and recorded on film. Finally, from the film, the data was printed on large photographic paper for display.

3.3.1 Michelson Interferometer Construction

Because of the creative nature of this research as well as requirements to work with a white light, not just any interferometer would work. It was decided that the necessary interferometer had to be built specifically for this application. A thin, glass beam splitter with a 50% transmission – 50% reflection coating on one side was obtained (Edmund Optics, 25 × 25 mm, 50R/50T), and with this a rudimentary interferometer was constructed on a portable 18” × 18” aluminum optical bread board as shown in Figure 6. Both 1” circular plane mirrors were on laterally adjustable bases, and the ‘test’ mirror also on a tip-tilt mount. The beam splitter was also mounted on a laterally adjustable base with a further rotational adjustment to ensure the proper angles of reflection and transmission for the system. To ensure the optical paths between the two legs remained as close to equal as possible, a compensator plate of plain silica glass was inserted into one leg of the interferometer. This initial system was tested with a Helium-Neon (HeNe) laser, for

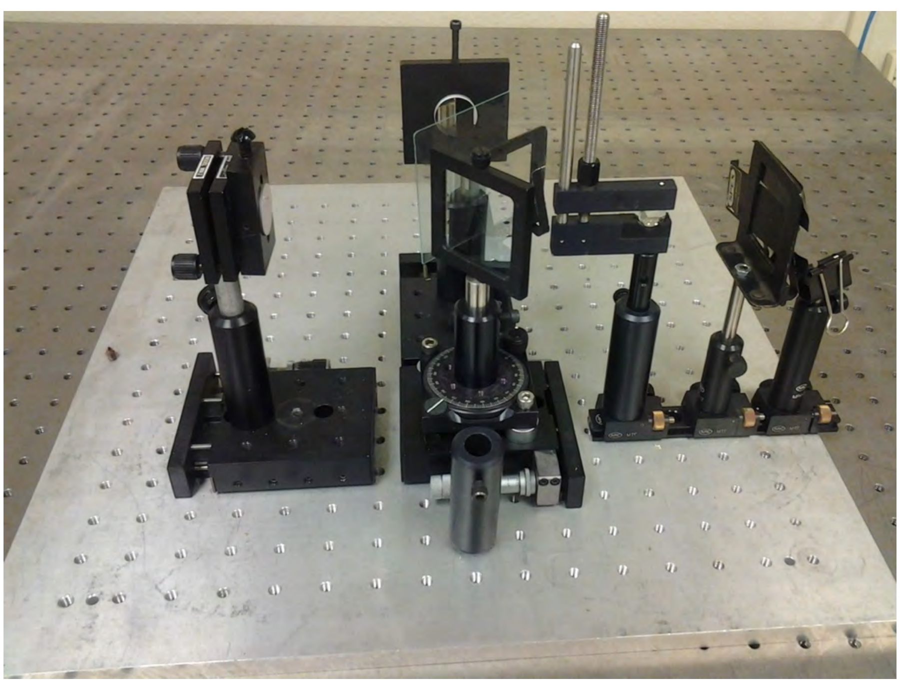


Figure 6 - Original Michelson interferometer on a portable optical bread board.

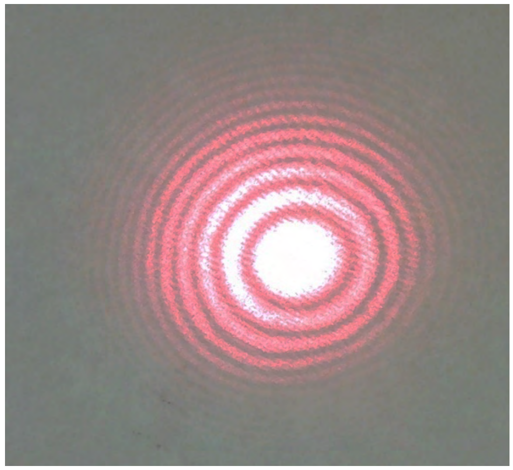


Figure 7 - Helium-Neon laser circular interference fringes obtained from the first Michelson interferometer constructed for this research on aluminum plate optical breadboard.

which a collimating system was constructed. The instrument was verified to be operational as typical circular fringes appeared (Figure 7).

Upon trying to find the zero optical path difference condition with the laser, several observations were recorded. Firstly, simply talking around the instrument would induce severe vibrations into the system. To reduce vibrations, the instrument and laser source were carefully moved and reassembled on a much heavier, more damped 4’ × 8’ × 1’ Newport optical table. In addition, it was discovered that determining the zero optical path difference condition was not feasible with only the coarse adjustment of the moveable mirror’s lateral translation base. A differential micrometer (ThorLabs manual drive, 1” differential adjuster - DM12) position adjuster was procured. Furthermore, to ensure the differential micrometer was indeed making changes when doing fine adjustments, a dial indicator gauge (Federal, C8IS .001”) was added to the system to simply track the test mirror as changes in optical path length were made. Figure 8 shows the dial indicator’s position in the system on the back of the moveable mirror, and below it the

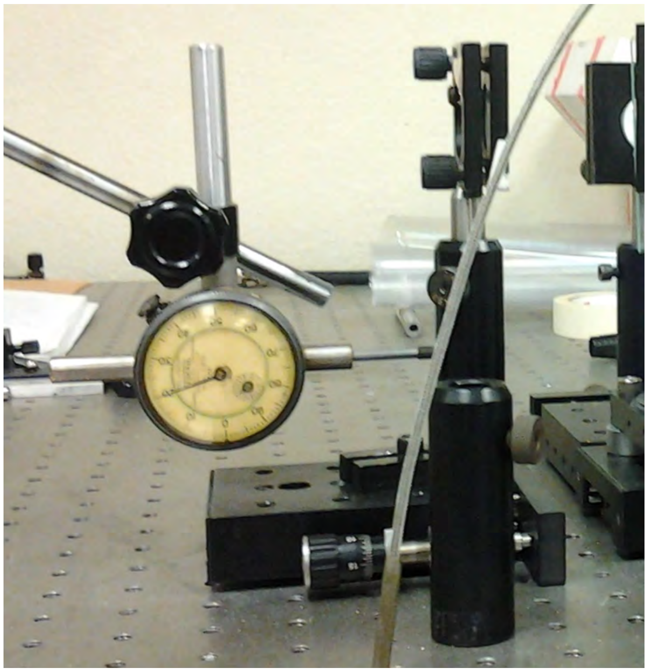


Figure 8 – (Left) Dial indicator in position tracking the moveable mirror. The differential micrometer can be seen below the mirror on the translation base.

Figure 9 – (Right) Close view of the differential micrometer's fine and coarse adjustment dials.

differential micrometer can be seen mounted on the translation base. Figure 9 shows a closer view of the differential micrometer’s dials.

3.3.2 White-Light Source Addition

Before the white light source was even added to the system, a special cart was procured to house it for the duration of experimentation. The fan motor employed to cool the tungsten-halogen light bulb of the fiber source shook when operating and thus needed to be separated from the vibrationally sensitive optical components on the optical table. A custom mount was constructed to direct the fiber cable’s output into the system through a 1 mm diameter pinhole screen. This pinhole effectively changed the source to be extended, fulfilling the requirement for a Michelson interferometer. A collimating lens was placed in alignment with the pinhole’s output to direct light into the system. The placement was laterally adjusted in such a way to completely fill both mirrors. To prevent extraneous rays from entering the system around the collimating lens, and opaque mask was placed around this lens to block them.

3.3.3 Finding White Light Fringes

As this time the system could receive both laser and white light source input with a simple switch. Using a HeNe laser, a position very close to zero optical path difference between the mirrors was found using solely coarse adjustments to the moveable mirror. This position is visually indicated by the appearance of tight, straight-line fringes with very little or no curvature (Figure 10).[41] Once the near-zero optical path difference location was established the source was changed to white light. The system's imaging lens was removed and a large sheet diffraction grating (calculated to be 1000 lines/mm) was put in its place. Noting the indicator dial's initial position, the white light source was switched on. As expected, no interference was noted. Using the

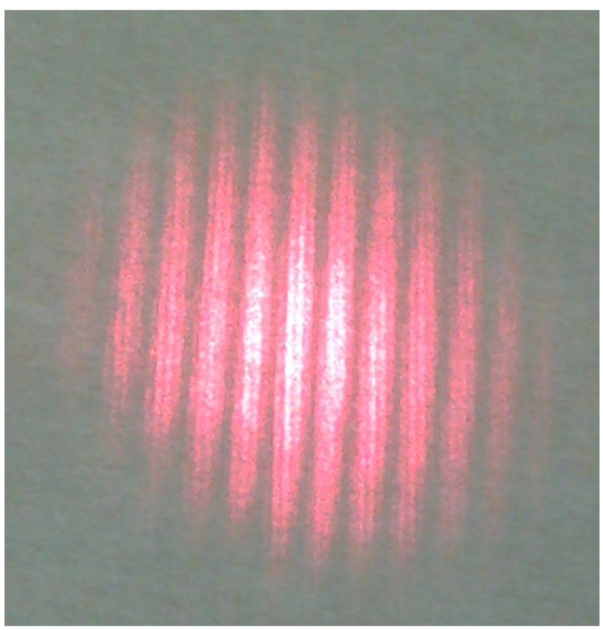


Figure 10 - Straight line fringes produced by this system using a HeNe laser source indicating the near zero optical path difference location.

technique detailed by Bell and Tubbs[42], systematic fine adjustments to the moveable mirror's position were made while viewing the first order spectrum through the diffraction grating. If an initial coarse position did not yield any fringes, the mirror was moved to a slightly adjacent coarse position to repeat the search through the fine positions. When the position was correct, destructive fringes appeared in the form of vertical, black bars through the first order spectrum (Figure 11). From there, using further fine adjustments the dark fringes could be moved to the mirror's surface. Looking at an oblique angle one could see the white light fringes and their colors on the mirror surface. By removing the diffraction grating and replacing the imaging lens, the white light fringes were imaged and projected from the system (Figure 4). Like the fringes created by the laser at the zero optical path length position, the white light fringes were similarly straight.

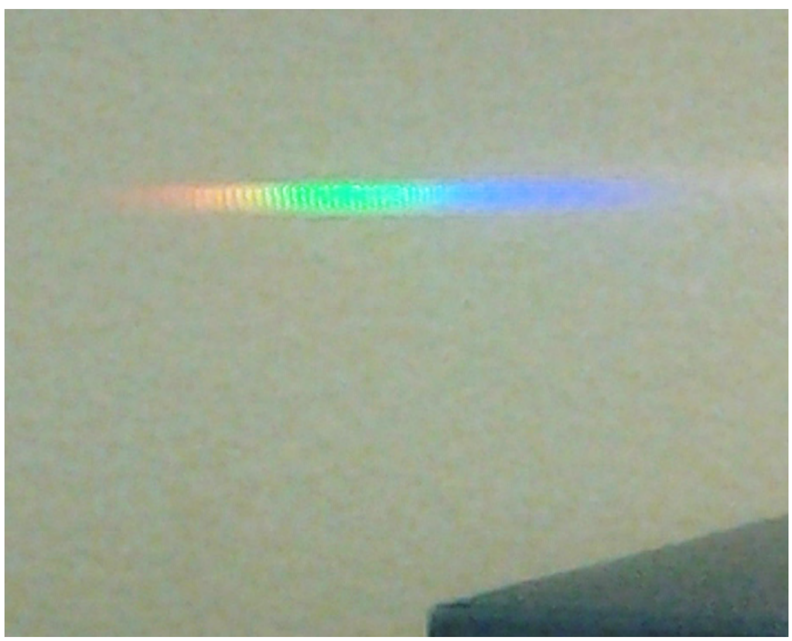


Figure 11 – Destructive fringes seen as dark band in the first order spectrum. Imaged through the 1000 lines/mm diffraction grating employed in finding these fringes. Digital photo by author taken on author's interferometer.

3.3.4 Creating a Light-Tight System

Due to the nature of color darkroom photography, the chosen recording method for this research, the room in which film and/or paper exposing takes place had to be light-tight. Thus, once the white light fringes could be seen exiting the system, a housing to block any extraneous light from the system had to be made for both the interferometer and the light source with proper outlet for the fringes to exit and opening for the fiber source. Measurements of the interferometer dimensions were taken. Plywood was cut to size to form the walls and top of a rectangular cuboid. The corners were reinforced with 2” x 2” beams cut to size. Special measurements of where the image would come through and the source fiber cable enter were taken. A medium sized hole was drilled in the front wall of the box to accommodate the projected image. A necessary requirement of the housing was it needed to have the ability to be removed to adjust the interferometer components at any time. Therefore, for the source, a rounded slit was cut in the side wall of the box. The slit would allow a narrow entry for the fiber cable but also allow the box to be removed

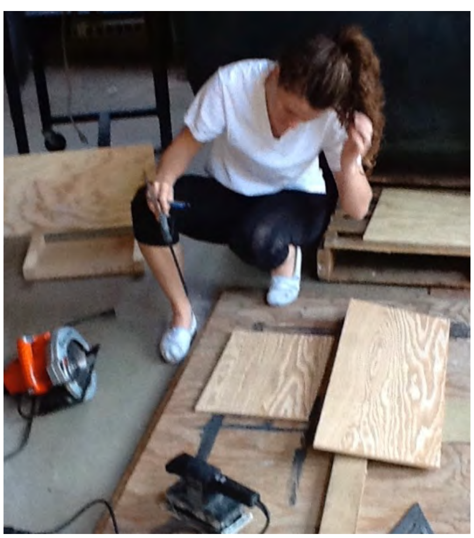


Figure 12 – (Left) Initial construction of the interferometer housing. Author pictured.

Figure 13 – (Right) Unpainted assembled housing showing details of imaging hole and shutter rail notch. Fabric drape for source slit also pictured on right.

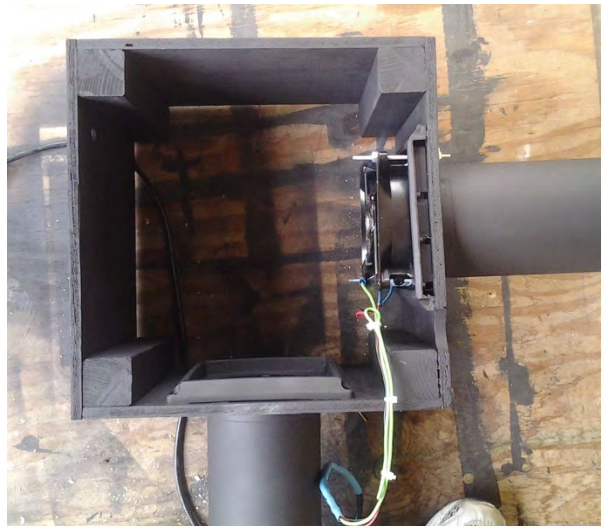
 

Figure 14 – (Left) Painted interferometer housing with handles. Source slit can be seen on the right, imaging hole on the left.

Figure 15 – (Right) Painted light source housing showing airflow ducts and fan. Lid to be attached still.

when necessary as the cable would just slide out of the slit. A piece of heavy black fabric would be wedged around the cable when the box was in place to block any light that might find its way out the slit. Finally, a small notch was made in the front to accommodate the small optical rail that would in time hold the system's shutter. The pieces were assembled and painted flat black. Simple black drawer handles were mounted to the ends for easy removal. Any further leaks were then caulked and painted black.

The light source housing followed a similar construction with the addition of airflow ports to prevent overheating. Plywood was measured and cut to the dimensions of the light source. A small hole the exact diameter of the fiber cable was drilled in the front wall of the box to let the cable through without causing light leak. In the back and one side wall, larger holes were drilled. Flexible aluminum ventilation pipes were mounted to these holes. Finally, a small slit was cut in the back to allow the electrical plugs to exit. The box walls were reinforced with 2" x 2" boards in the corners and assembled. All parts of the partially assembled box including the exit port pipes were then painted flat black. To be certain the source would not overheat, a special fan was constructed for the source housing. The fan was wired to a common electrical plug and grounded to the box. With the fan mounted into the exit pipe, the source was inserted and tested. To complete the source housing, the lid was fixed on the box. Flexible, reflective piping was added to each exit port to allow air flow but effectively scatter any light that might make it through the ports. Upon completion of the source box, all unnecessary light was nullified but airflow around the source was not compromised.

Additionally, special coverings had to be made to block all window light and light leaks from doors. Window blocks were cut to cover the windows exactly and painted flat black. To block light from entering around doors, heavy black material was procured and bunched around the leaks. Any additional instrumentation with lights was covered by either thick, black material or turned off when applicable.

3.3.5 Shutter System and Recording Assembly

With the system fully housed, several test shots at various exposure lengths were taken. These tests were recorded directly onto color darkroom paper in total darkness as was the original design of the research. Upon developing the test images two observations were made. Firstly, the crude shutter used to make the incremental exposures was not going to be able to produce the desired results. Almost all the test results were horribly overexposed indicating that a shutter capable of exposure times of less than a second to milliseconds – faster than human motor capability – was necessary. Secondly, the reverse color nature of the color darkroom paper was not yielding the color results desired. While many of the individual colors were lost in the over-exposure, what could be seen was surprisingly muddled and red toned. Based on these observations two new additions to the apparatus were made.

An old shutter assembly from a large format camera, sans the lens, was procured (Rapax, Wollensak, Rochester, NY 1-400). The mechanical components of the shutter were restored to seamless operation and the shutter release cable fixed. Once operational, the shutter was tested at various speeds confirming that it was indeed capable of increments far faster than one second. Upon completion of the restoration, the original shutter tube assembly was turned down to size using a metal lathe and drilled and tapped to ¼” × 20 thread (see Figures 16, 17). The shutter was mounted on the optical rail which held the imaging lens of interferometer albeit outside the instrument housing. This shutter was able to block all light coming from the instrument housing until which time the shutter was released to record an image. It could also be held open indefinitely or simply removed to compose images or adjust any of the interferometer’s optical components.

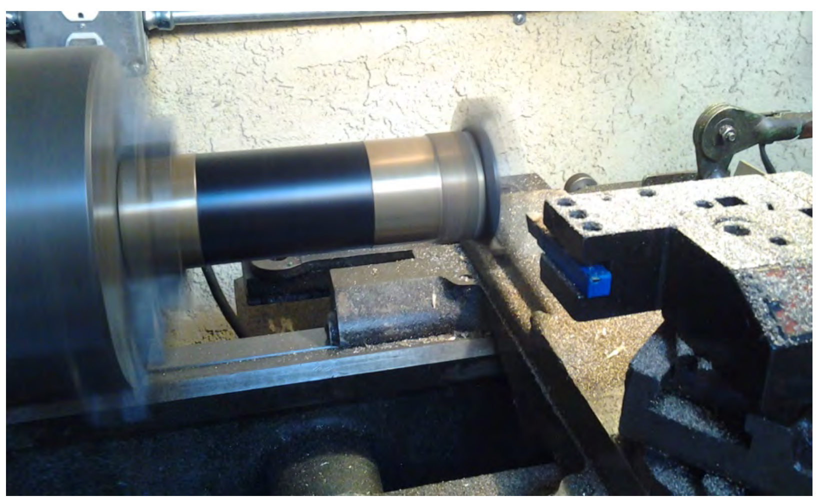



Figure 16 – (Left) Author turning the shutter assembly tube using a metal lathe.

Figure 17 – (Right) Closer view of the shutter tube assembly being turned to size on the metal lathe.

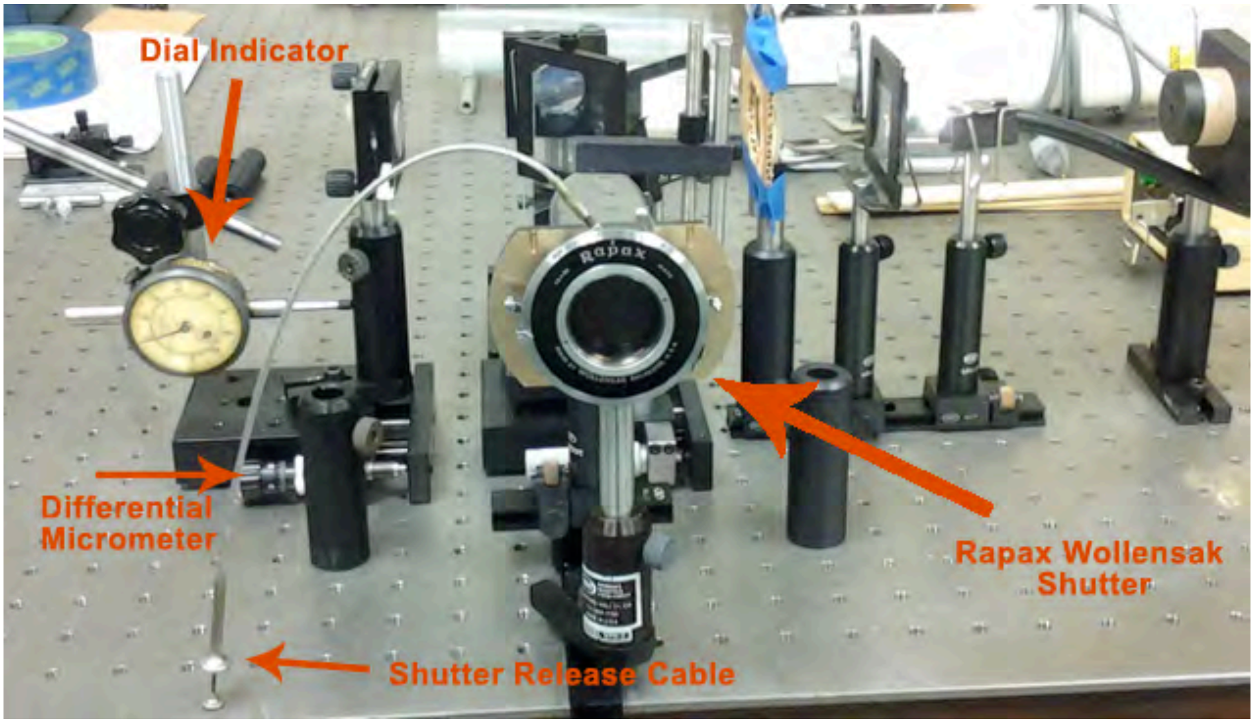


Figure 18 - The completed shutter assembly with the attached shutter release cable mounted in place following the imaging lens of the interferometer.

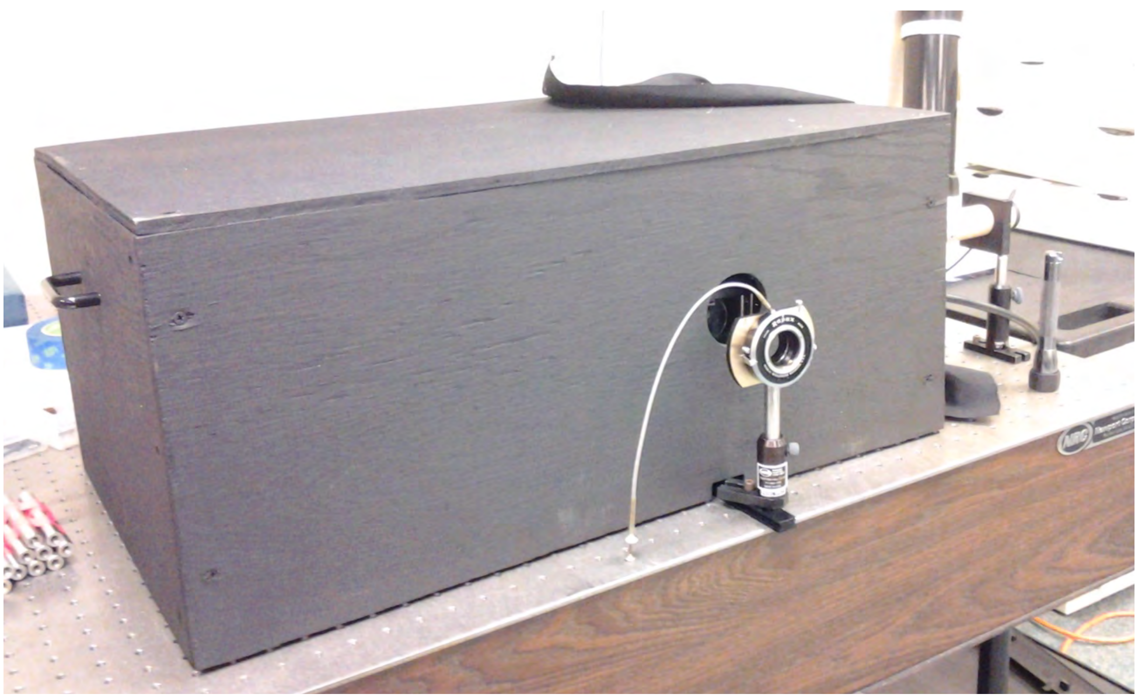


Figure 19 – Shutter assembly with the interferometer housing in place. The shutter was purposely designed to operate outside of the housing for easy access and manipulation.

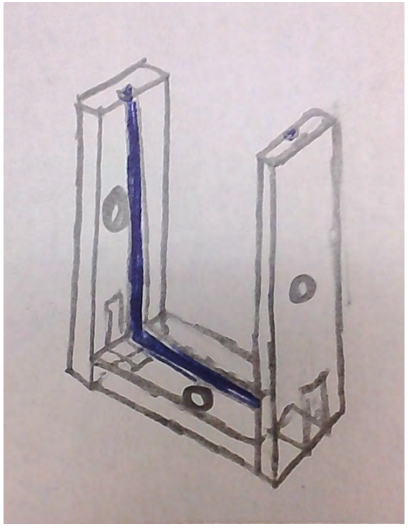


Figure 20 – (Left) Original design sketch of the film holder framework.

Figure 21 – (Right) Film holder in use. To view a specific composition, a white paper was placed in the holder.

Since recording the images directly onto color darkroom paper did not yield the color results desired, the method of documentation was altered slightly. It was decided that the positive colors of the white light fringes were desired. Therefore, the interferograms needed to be exposed directly onto film rather than color paper. Kodak Ektar 100 ISO medium format film (4” × 5”) was chosen to best preserve the high quality and color resolution. Medium format film holders were obtained and prepared for use. An assembly to carry these film holders on a variable position tripod was devised (see Figures 20-21). The side walls were constructed from wood beams with slits just wide enough for the holder to sit right in without blocking any of the film. The base was made of sturdy aluminum, drilled and tapped to ¼” × 20 thread for mounting on the tripod or optical table if necessary. This design allowed the film holder to be positioned at will while still allowing the dark slides - which protect the film until ready to expose - to slide in and out easily.

3.3.6 Film Exposure and Aberration Inducement

With the instrument and assemblies all completed, the process of recording the interferograms onto film was initiated. First, test images were taken at varying exposure times to determine the proper exposure time necessary. The film was developed and from these tests it was determined that an exposure time of anywhere between 1/50 to 1/25 of a second would yield a properly exposed image. Several straightforward images of the straight line fringes were created, as well as variations on and different compositions of the straight fringes.

Once images of the straight white-light fringes were recorded to contentment, various methods were used to induce aberrations into the system since the major goal of this research was to image aberrations utilizing white light interferometry. To begin, simple mechanical stress was applied to the mirrors of the interferometer. Small variations within the straight line fringes could be seen as a result of the stress. A few images of these stressed fringes were taken, but, by and large, the fringes were still mostly straight. Large amounts of tip and tilt were then applied to one of the mirrors. By doing so, astigmatism was introduced to the system and resulted in typical, but beautiful, saddle shape fringes (Figure 22). It was noted that by varying one of the mirror's position (changing the optical path difference between the interferometer arms) by a few micrometers

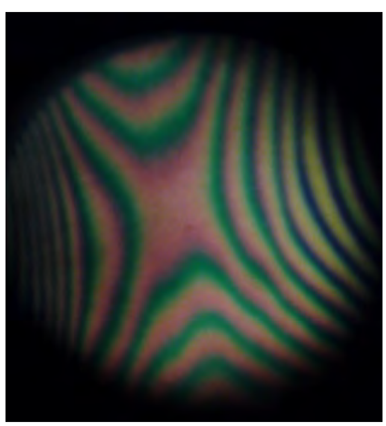
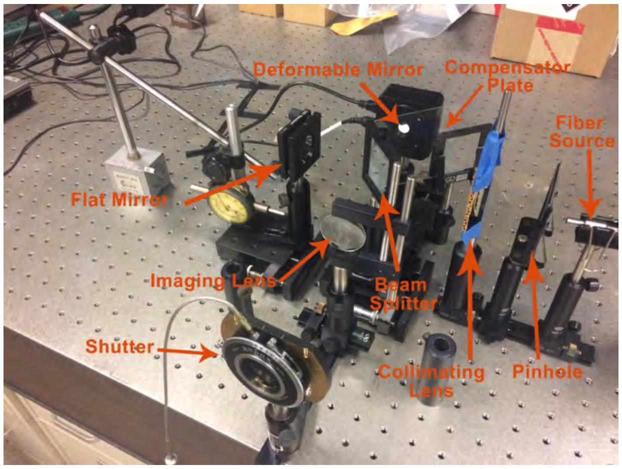


Figure 22 – Midfocus, astigmatic white light fringes as produced by tip and tilt variations of the mirrors in the Michelson interferometer.

several different color variations of the white light astigmatic fringes could be seen. Accordingly, several different images were recorded on film.

3.3.7 Deformable Mirror Implementation

Several other coarse methods to induce specific aberrations into the interferogram were tried. It was determined after these attempts failed to produce the desired results that a mirror surface with the selected aberration was necessary. Since most modern optical elements are constructed to eliminate aberrations as much as possible, a Thorlabs (piezoelectric deformable mirror – DMP40-P01) adaptive optics system was used in reverse to deform the nearly perfect incident wavefront in order to achieve white light interferograms of the various aberrations. The following changes to the system were made to accommodate this addition. It was first determined that in order to best see white light fringes of the various aberrations a high quality flat test mirror was necessary. The previous moveable mirror was removed and a new $\frac{1}{4}\lambda$ flat mirror was carefully installed. The deformable mirror was installed in the other arm of the interferometer. The electrical cords necessary to run the mirror were meticulously run and affixed to the optical table in ways that would not interfere with operations of the system. A small notch was cut in the interferometer housing to also accommodate these cords. Software to operate the deformable mirror was implemented on a laptop computer that could easily be run from the optical table or directly beside it in the case of vibrational sensitivity. With the mirror running the required voltage to have every segment be flat (100 V in this case), the rough mirror positions were further calibrated with a HeNe laser source in search of zero optical path difference. When straight line laser fringes were obtained the laser was replaced with the white light fiber source. Following the same procedure



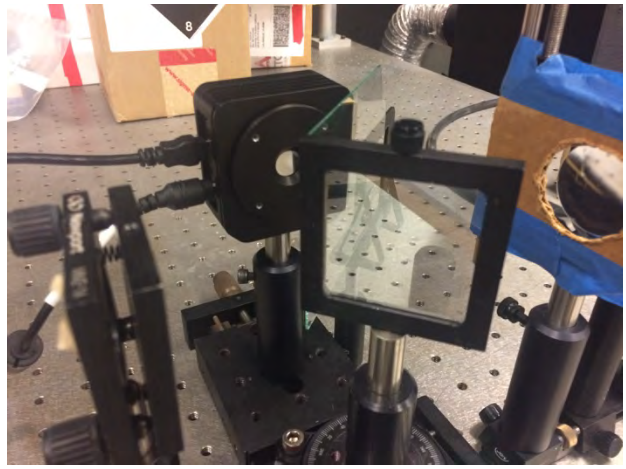


Figure 23 – (Left) Full interferometer system including the new deformable mirror implemented in the rear mirror position.

Figure 24 – (Right) Close up showing detail of the new deformable mirror implemented in the system.

as detailed by Bell and Tubbs[43] and previously followed in this research, the diffraction grating was reintroduced into the system and the test mirror meticulously laterally moved in micrometer increments. Once the dark fringes could again be seen in the first order spectrum of the diffraction grating they were slowly moved to the mirror surface. From there the nearly circular white light fringes were imaged out of the system. The moveable mirror's coarse adjustments of tip and tilt did not allow for much change while keeping the fringes visible, but the fringes were eventually centered in the projected image. By adjusting the differential micrometer on the base of the moveable mirror to change the optical path difference, different colors of the fringes could be seen and cycled through. Several images of these circular fringes in different color variations and compositions were taken both on 4" × 5" film and digitally.

Using the accompanying software, small, incremental amounts of single aberrations (in the

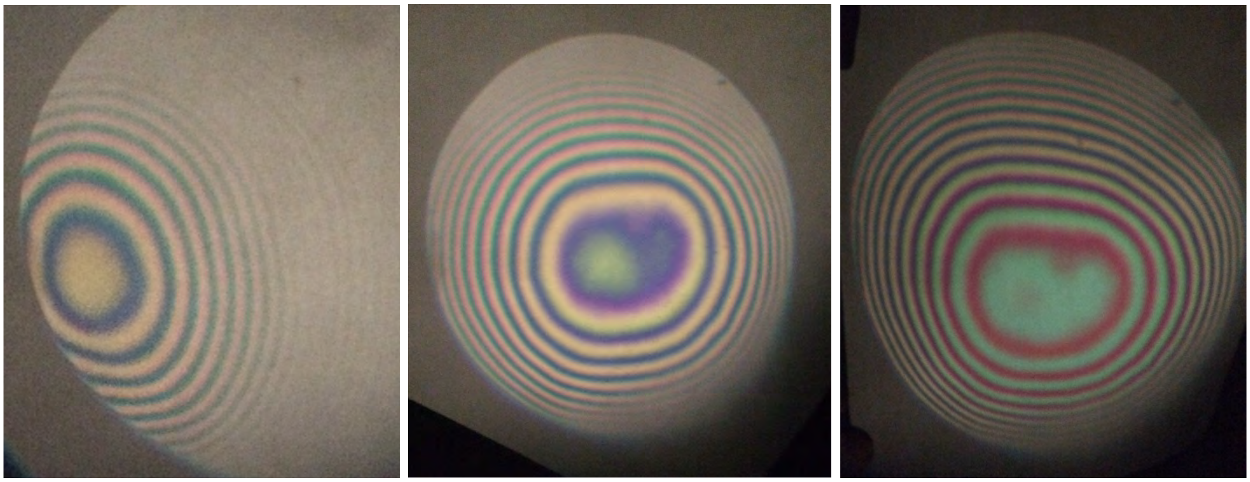


Figure 25 - (Left) Original, circular, white-light fringes produced by the system with the addition of the deformable mirror. The first order fringe (navy blue/black) is centered.

Figure 26 - (Center) Using tip and tilt adjustments of the moveable mirror the circular white light fringes were moved to the center of the view. Small, likely astigmatic, deformities can be seen as a result of the tip/tilt and have moved the first order fringe one position out.

Figure 27 - (Right) By adjusting the moveable mirror laterally a few micrometers, different color fringes could be seen cycling through the view as a result of the mirror position and the changing optical path length. Here the mirror was adjusted to showcase the magenta and turquoise fringes.

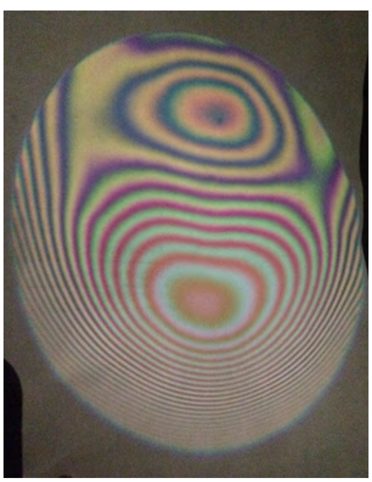
form of Zernike polynomials[ii]) were introduced to the deformable mirror's surface. As the deformation of the mirror surface was changed, the moveable mirror position also had to be adjusted slightly to maintain near zero optical path difference and keep the fringes in view. Though strikingly interesting at all amounts of deformation, the most aesthetically pleasing fringe pattern was often formed at large or maximum contortion. When a suitable interferogram was acquired, the film was set up to create the most interesting composition and recorded. A digital record of each composition that was recorded on film was also kept. Additionally, a contour map of the

---

[ii] The ThorLabs software to run the piezoelectric deformable mirror employed in this research uses a slightly altered labeling system for Zernike polynomials. In the software interface, all Zernike polynomial numbers are shifted by one so that the polynomials start at one (Z1) instead of zero (Z0). The software seems to have switched axes from standards as well. The aberrations are labeled in accordance with their ThorLabs software names and axes. Literature equivalents can be easily extrapolated knowing these specifications about the software, and by simply viewing the results.

deformable mirror's surface was recorded for each composition. Though the mirror has the capability to deform along multiple axes (and these variations were often explored) typically one would produce better, or more aesthetic to the nature of this research, results than the other. The digital form of a coma aberration deformation along with its accompanying mirror map detailing the surface of the deformable mirror at the time of recording are shown in Figures 28 and 29. The contour map of the deformable mirror uses a specific color scheme to denote a local convex or concave on each specific section. When the mirror section was in the neutral or flat position (denoting a default 100 V through the section) the contour map showed an orange color. As a section became increasingly convex the color cycled from orange through yellow to the maximum (200 V) of white. Similarly, the map denoted a section becoming increasingly concave by successively changing from orange through red into the minimum (0 V) of black.

Observing the coma pattern set (Figures 28 and 29), it can be seen that the local convex sections on the bottom of the mirror map (as indicated by light yellow to white actuator sections)



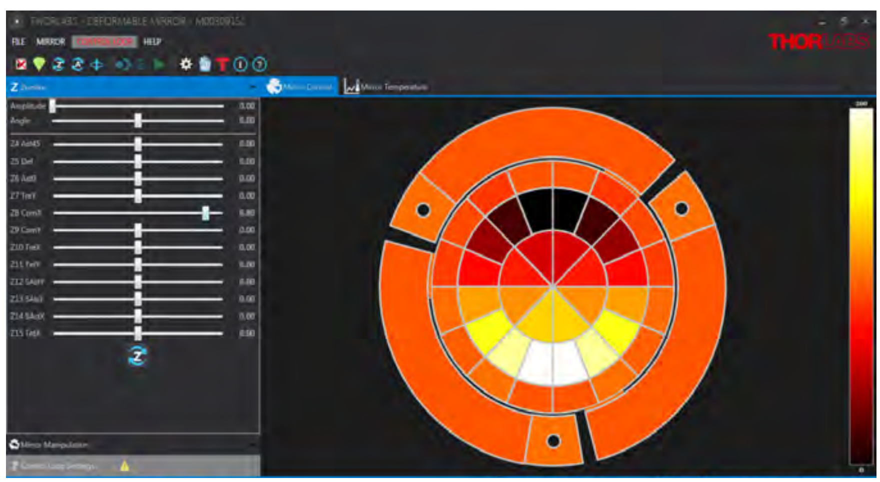


Figure 28 - (Left) Digital image of the second coma (x-axis) aberration (ComX - Zernike Z8 ThorLabs software) as recorded at the time of film exposure.

Figure 29 - (Right) Mirror map showing the contour of the deformable mirror with the amount of coma aberration present at the time of film exposure.

correlates to the blue/teal and magenta interference fringes on the bottom of the digital image. Similarly, the top of the mirror map indicates a local concave where the segments are black and/or dark red and correlates to the first order fringe that can be seen near the top of the digital image. While optical path difference due to local concave or convex of the deformable mirror does partially determine the color separation in a specific location in the image, it is also determined by the coarse lateral optical path adjustments of the mirror itself. Translating the test mirror a few micrometers could move the first order fringe from the top circular fringe pattern of this coma image (Figure 28), through the middle, and to the lower circular fringe pattern. More digital images of the recorded aberrations and their corresponding deformable mirror contour maps are presented in the Appendix.

Upon completing exploration of the single, primary aberration deformations to the mirror surface, combinations of aberrations were placed on the mirror. If a combination yielded an exceptionally interesting fringe pattern, the above procedure was followed – the interferogram was recorded on film, a digital image taken, and a mirror contour map saved. Due to the high deformations of the combination aberrations often the moveable mirror's lateral position, tip, and tilt had to be adjusted. While best contrast was noted near the first order fringe, these variables were often adjusted to purposely achieve certain compositions and fringe color variations during this phase of data collection.

It is interesting to note here the variation between the digital image (and what the human eye could see emanating from the interferometer) and the image that the recording device – medium format film – 'saw.' While much of the spectral variation remains the same, often the film picked up a color cast invisible to the human eye. Other times what the human eye perceived as black or white was in fact a distinct color that only with the sensitivity of the film could be seen after the fact. This was most true of the first order fringe which appeared black to the naked eye, but blue or navy blue to the digital cameras and film. The resulting variances by no means discredit or place higher ‘realism’ value on either the digital image or film image. It simply highlights the differences in resolution and color responsivity between the human eye, a digital CCD camera, and the medium format photographic film.

3.4 SIGNIFICANCE OF LIGHT AS THE PHOTOGRAPHIC SUBJECT

Light is essential. Without light, no photograph can be recorded. Without light, the stage actor becomes a mere voice in the darkness. Without light, the smart phone becomes a fancy piece of plastic. Without light, the day is eternally night. Light, and how essential it is – to not only our way modern way of life but also to contemporary art and science – is not a thing that often crosses our minds. We use and expect light in most everything. The year 2015 was declared a ‘Year of Light’ by the United Nations to raise awareness of and promote achievements in light based science and its applications, and how these technologies “provide solutions to global challenges in energy, education, agriculture, and health. Light plays a vital role in our daily lives and is an imperative cross cutting discipline … in the 21st century.”[44] Light and the study thereof are means by which the global society can unify and strive together towards a better tomorrow. With a heightened recognition of light and light based technologies, there is no better time to explore the possibilities using light as the photographic subject. When one can actually see light in its simplest form (waves), it opens doors of understanding and creativity to use this powerful tool in other groundbreaking ways. It challenges the status quo both artistically and scientifically, urging practitioners to step into this new integrative era. Light as the photographic subject is not a totally new phenomenon, but it ushers in a contemporary society willing to embrace interdisciplinary thought which is of upmost importance for the future.

CHAPTER 4 – *On the Bright Side*

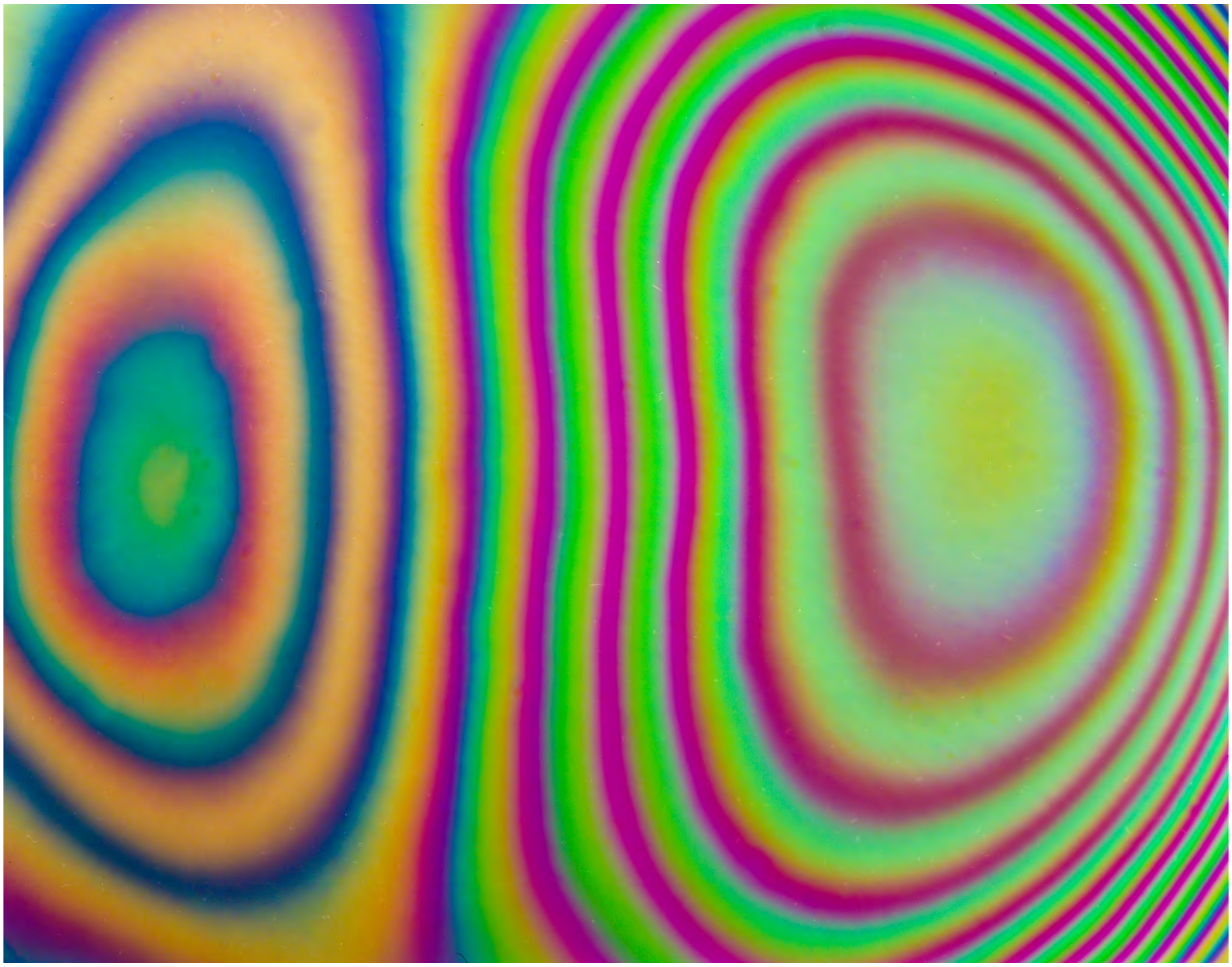
4.1 ARTIST'S STATEMENT

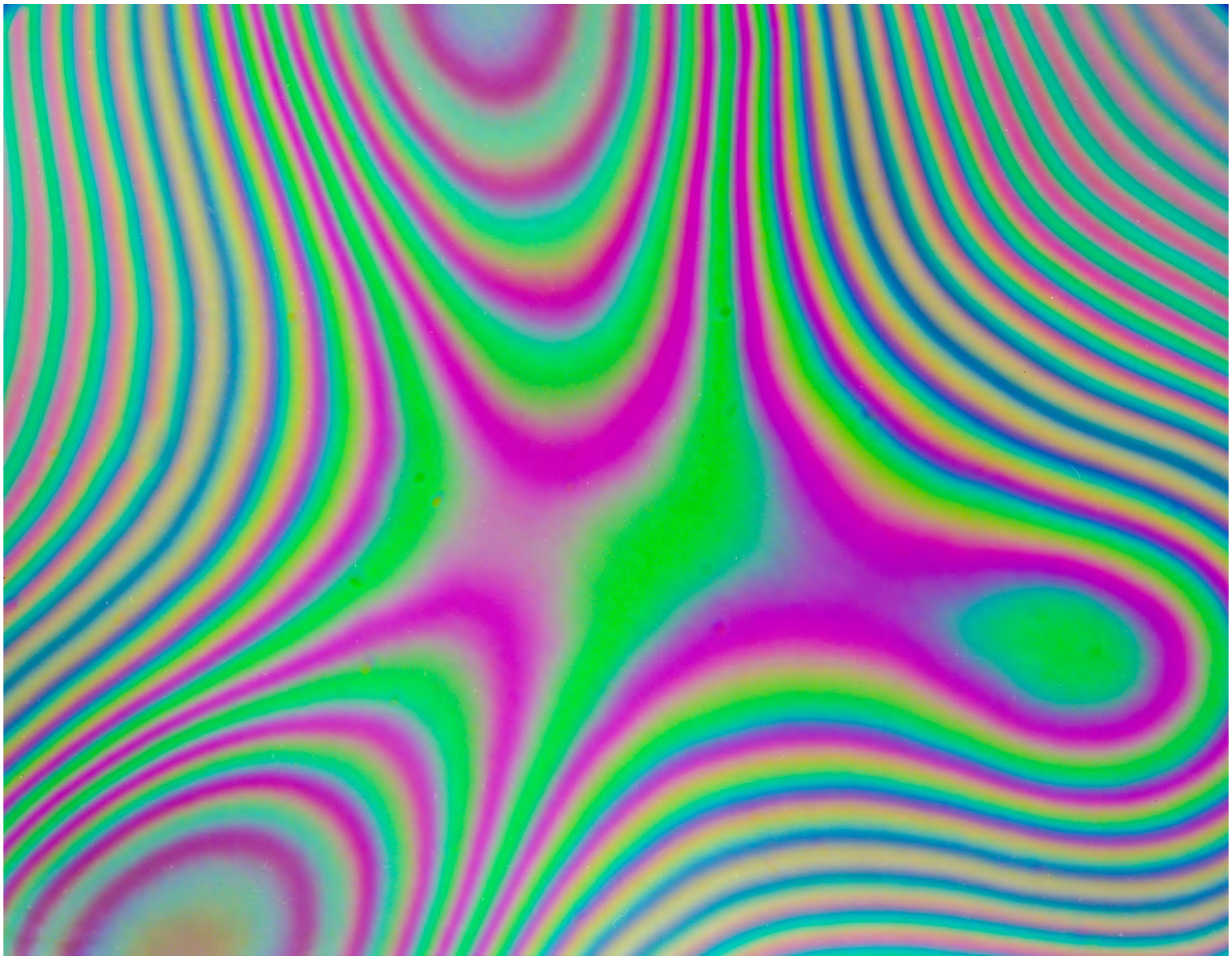
It's true; a lens was never intended to distort the image so it becomes unrecognizable. In fact, for the majority of art/optics history, the primary purpose of the camera system was to deliver highly realistic imagery. But it's also true that the distorted image has intrinsic beauty which would have been missed if the lens wasn't dysfunctional. Like impressionist artisans of old who challenged the realism status quo, here the unstated 'rules' of photography are broken. Image sharpness is completely foregone to showcase the overall visual effect of a, by-modern-understanding, defective camera system, and white-light interferometry is employed to produce an intense and unshaded color vibration. From the distinctly formal optical science techniques to the time-honored, fine art photography compositions (medium format film), this blended work encapsulates the essence of impressionist thought but in the contemporary era– a new way of seeing, a fresh and original vision.

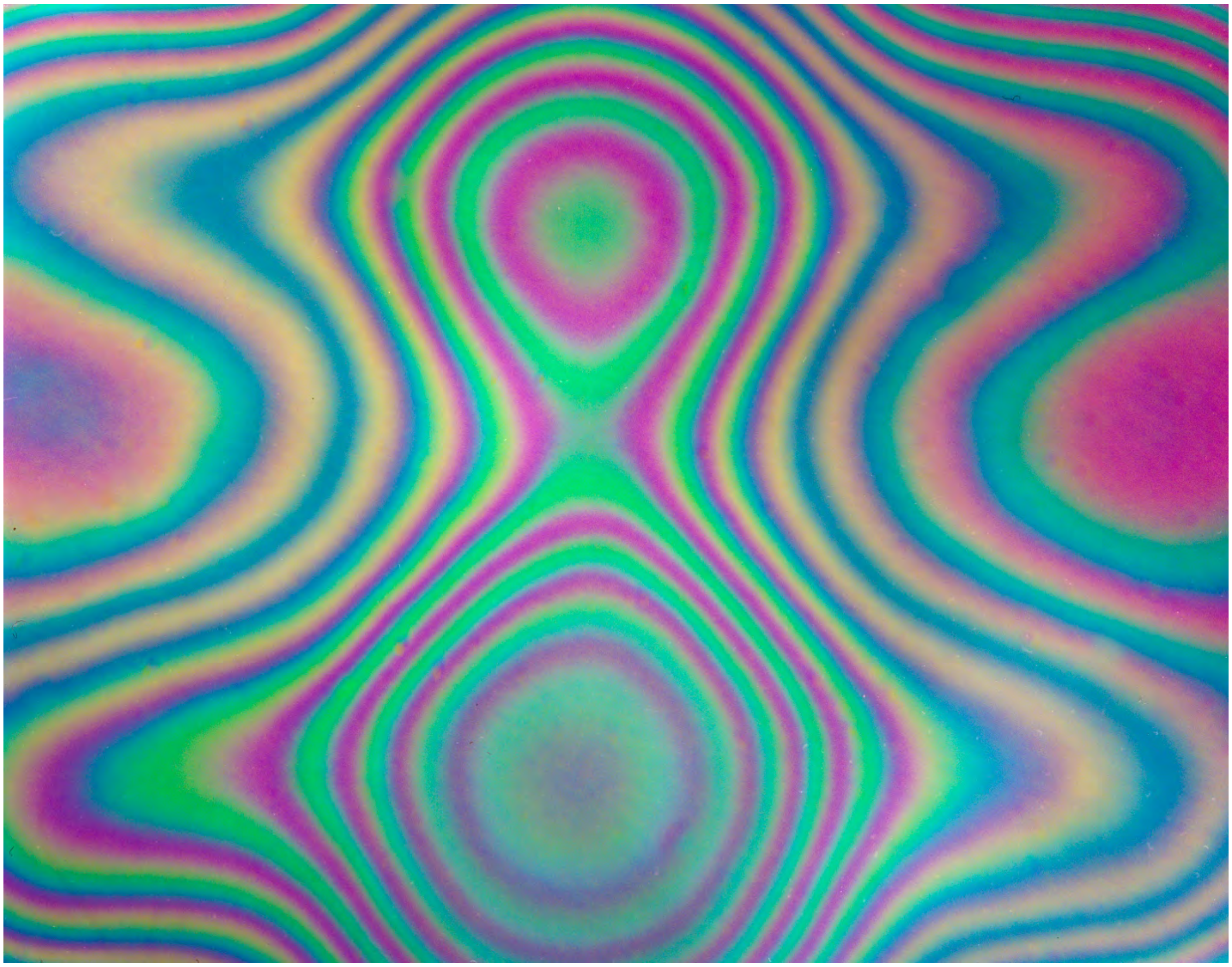
On the Bright Side is not purely science or purely art as they are currently defined – it's both. It's a stunningly vivid and distortion-filled invitation to all, regardless of background in science or art, to step beyond convention and into an avant-garde age of interdisciplinary innovation.

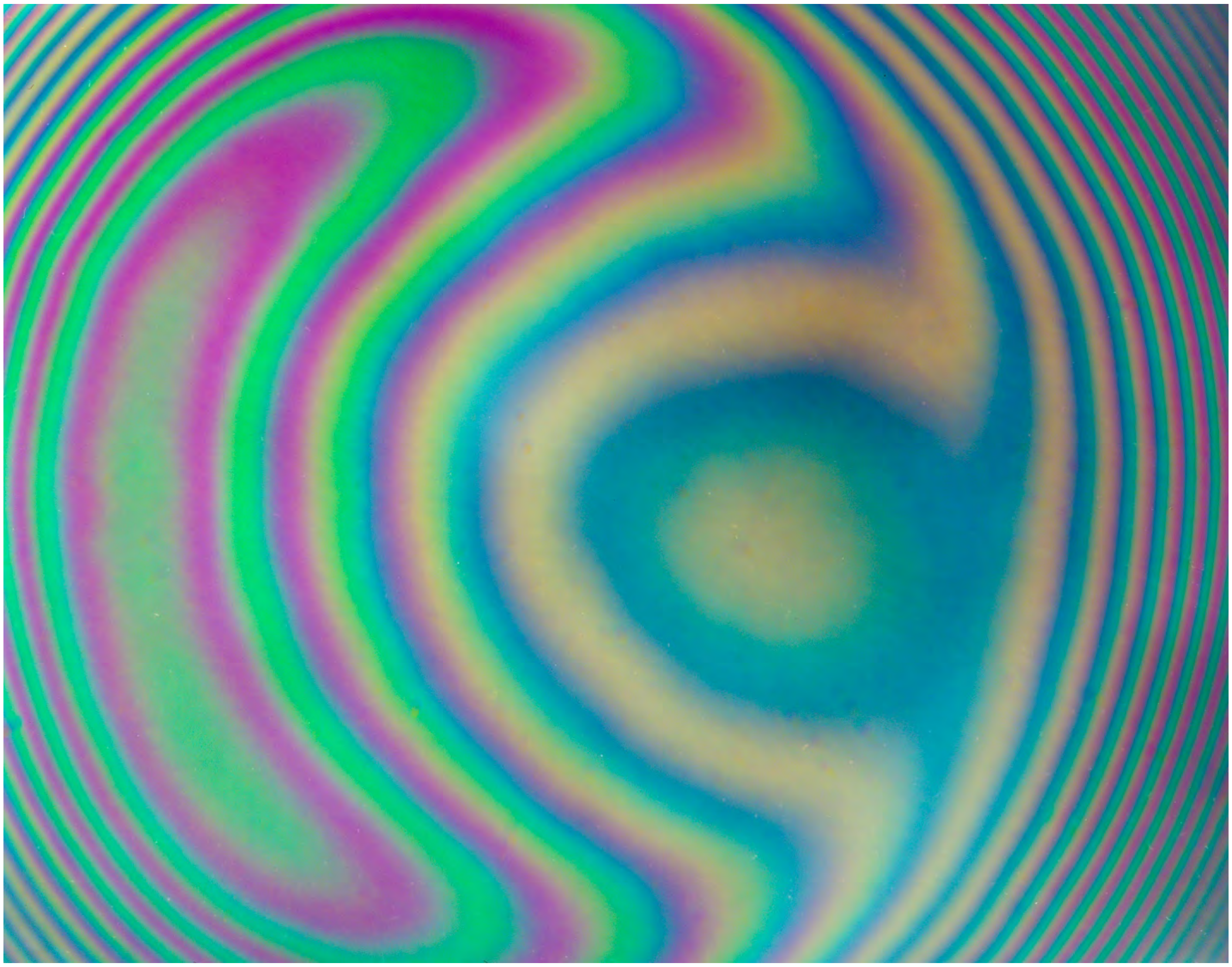
4.2 FORMAL DISPLAY

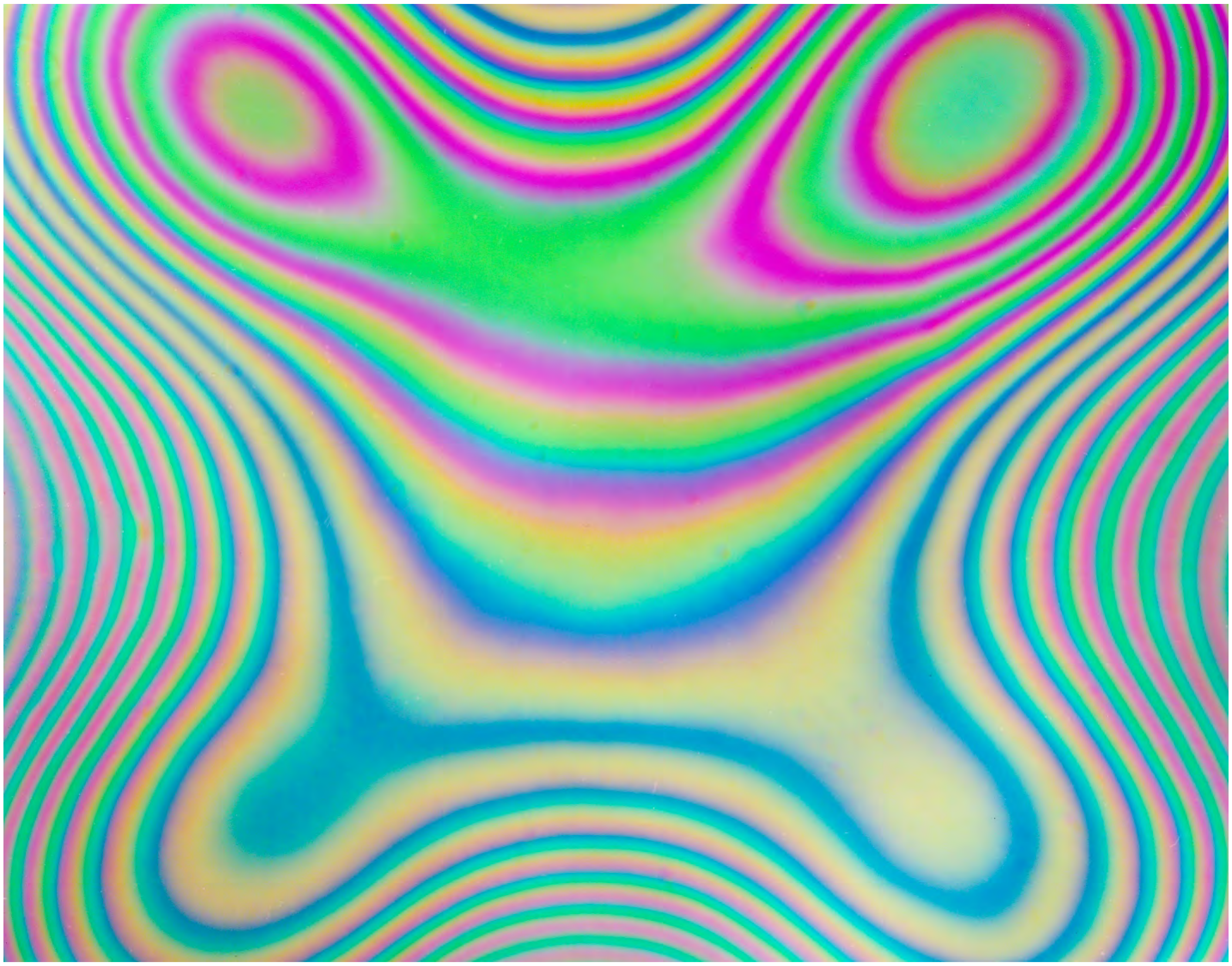
(*On the Bright Side* is subsequently presented without titles or detailed explanations. While each image has a highly sophisticated creation account, this body of work is designed to be contemplated and enjoyed based solely on the pieces themselves.)

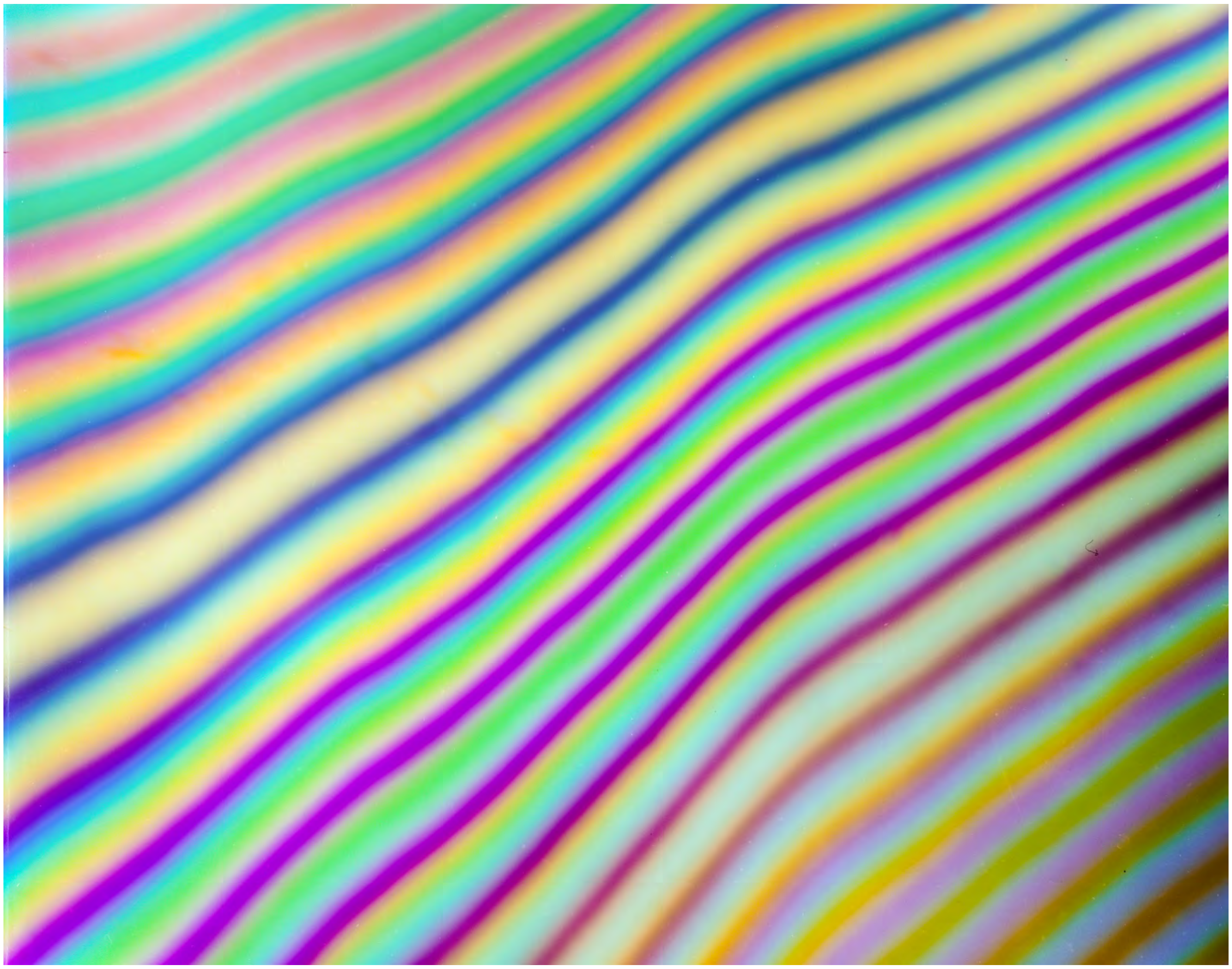


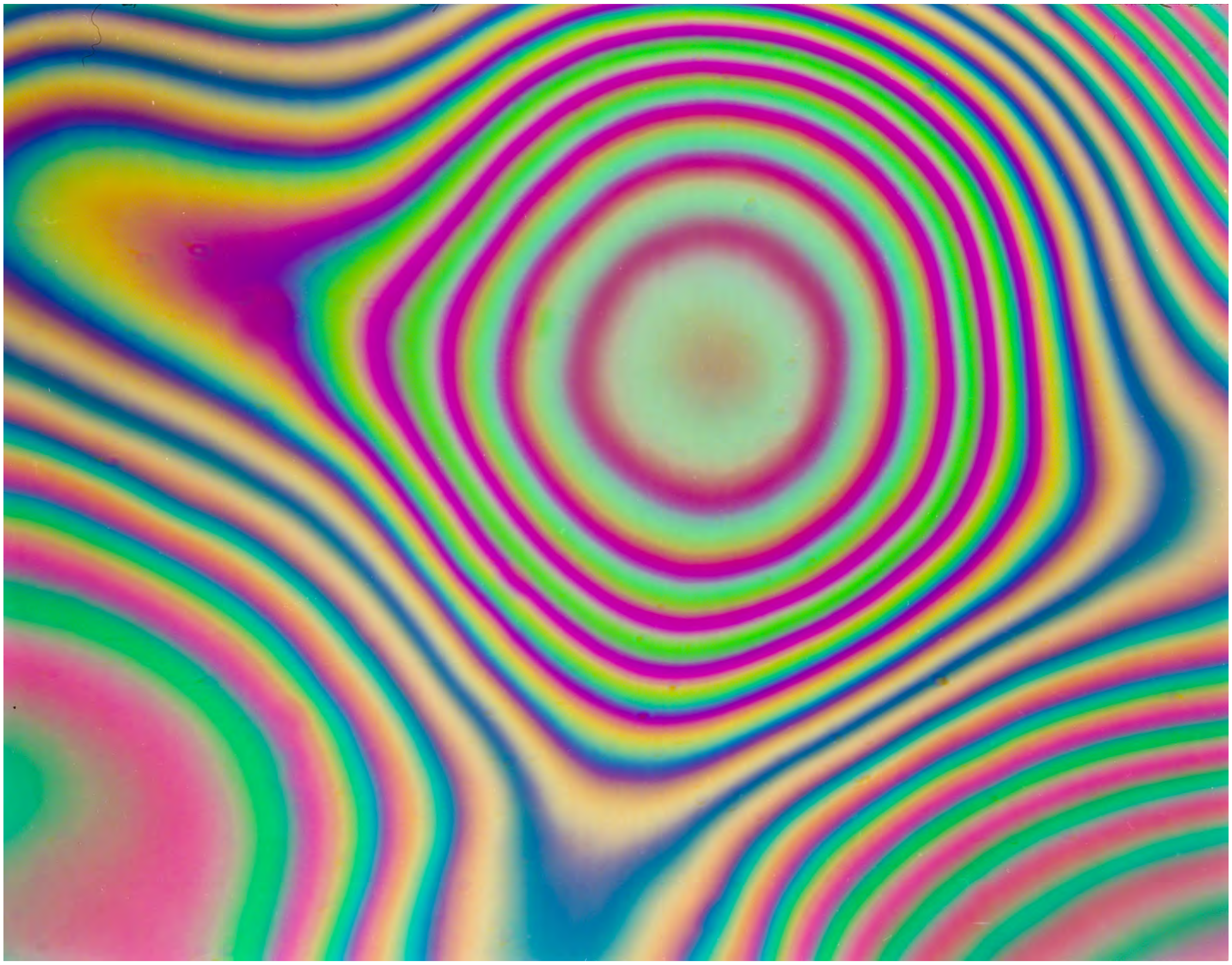


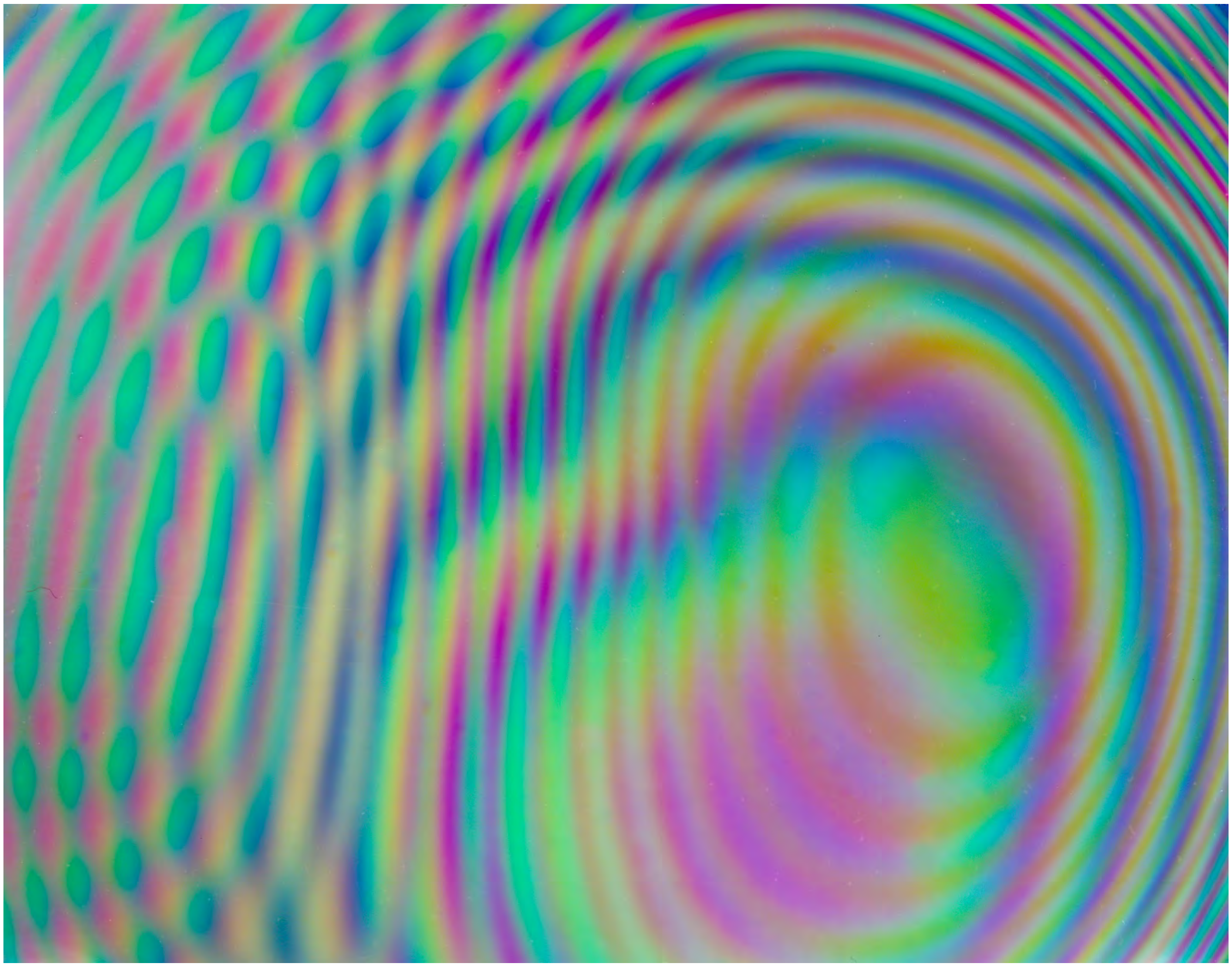


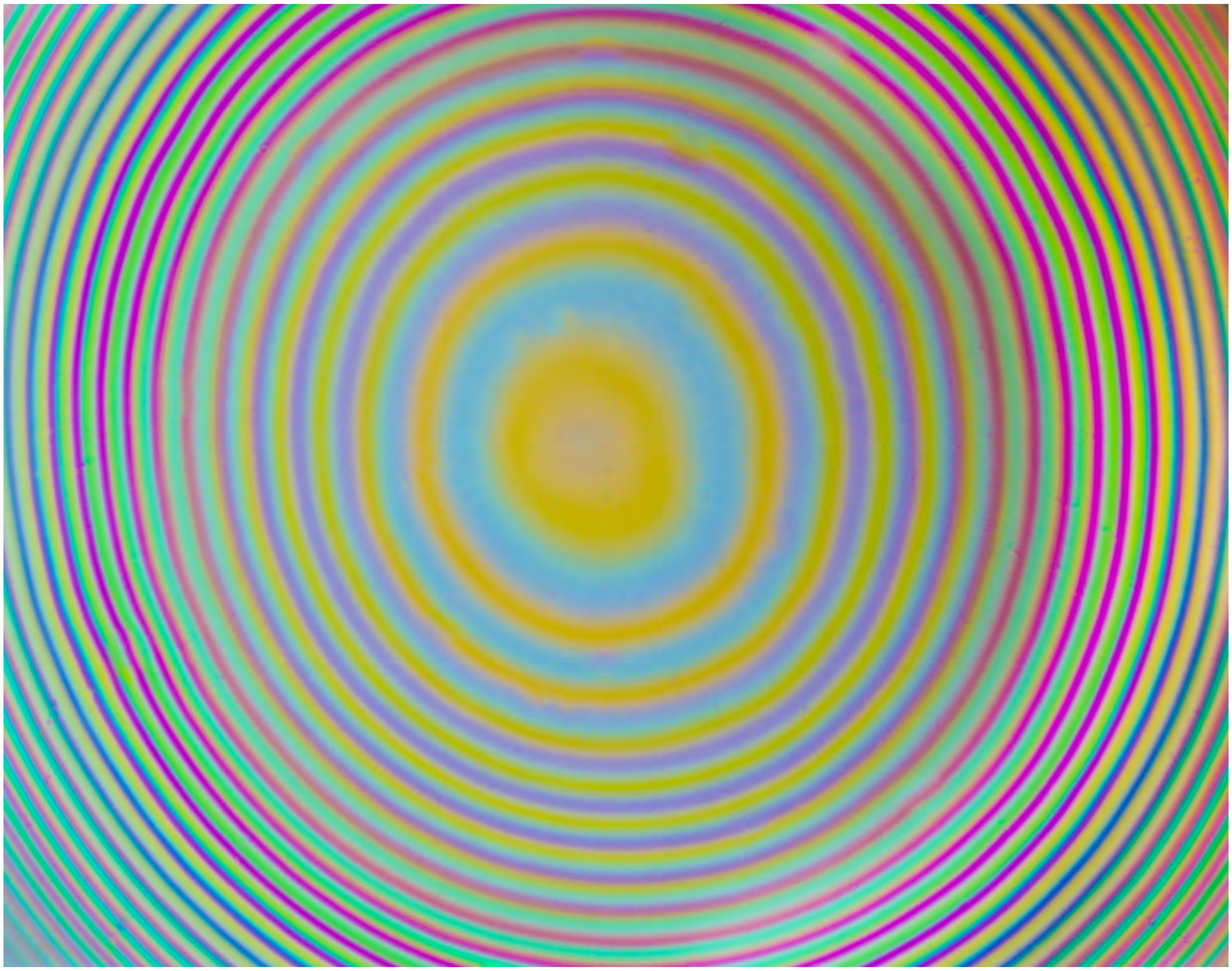


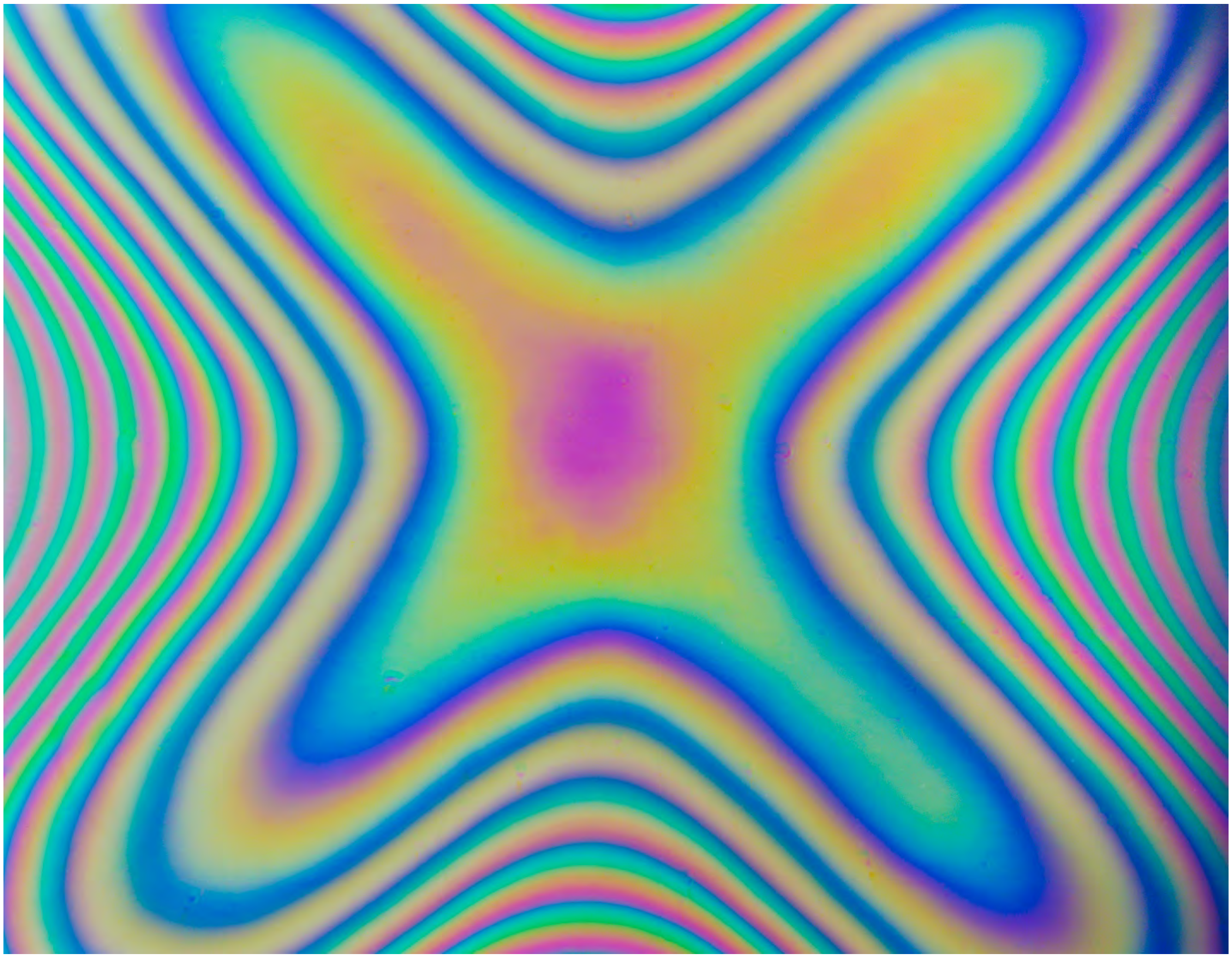


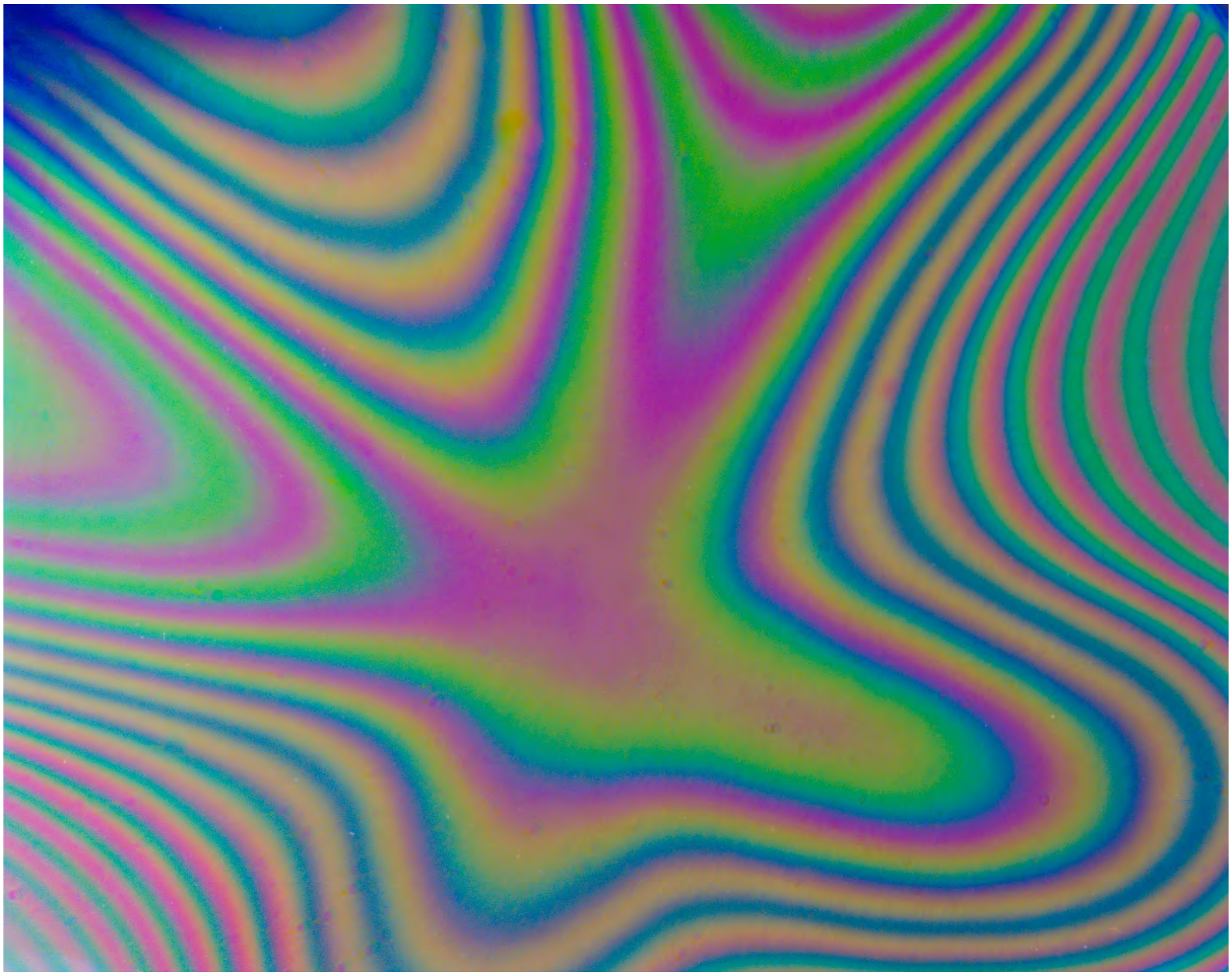


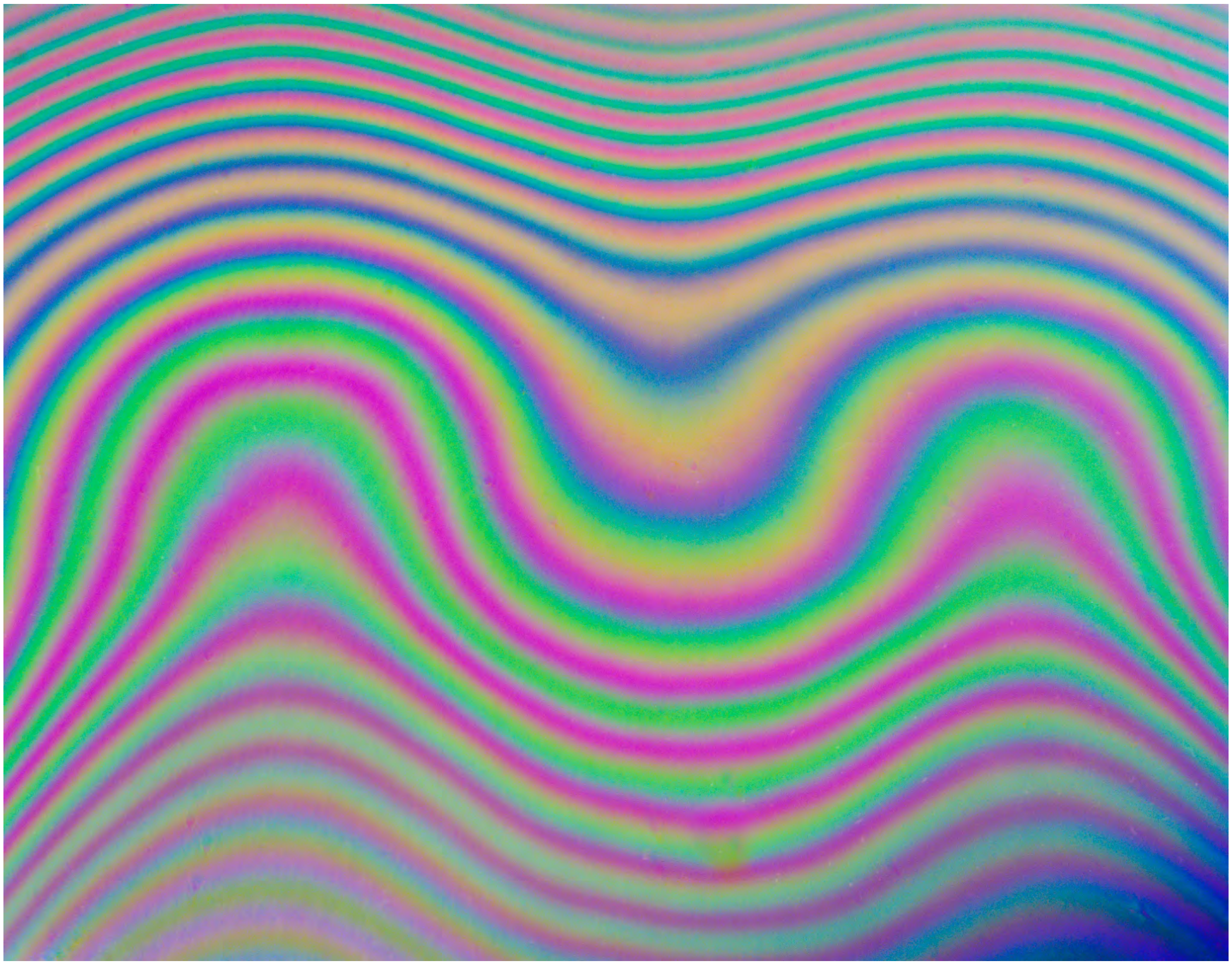


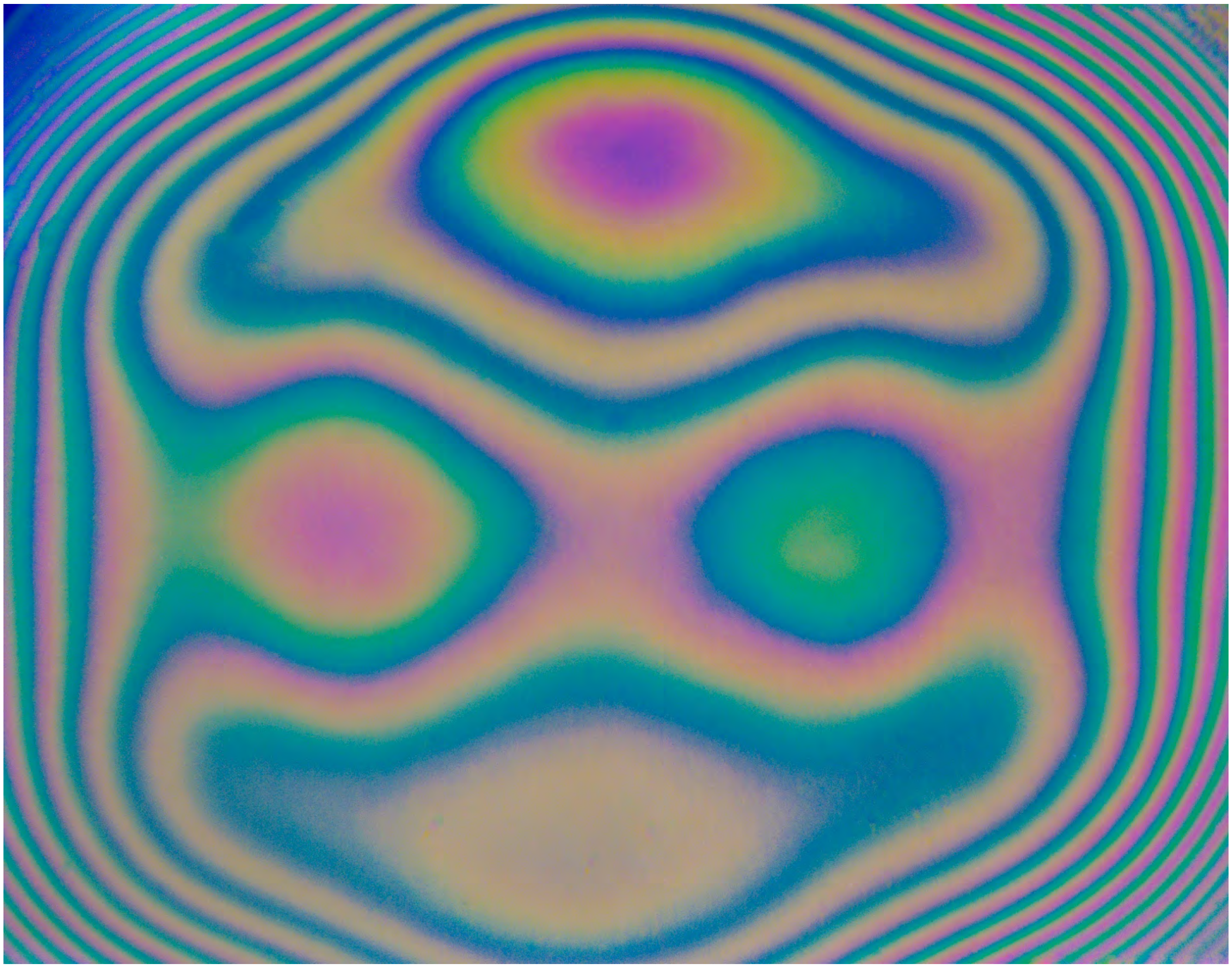


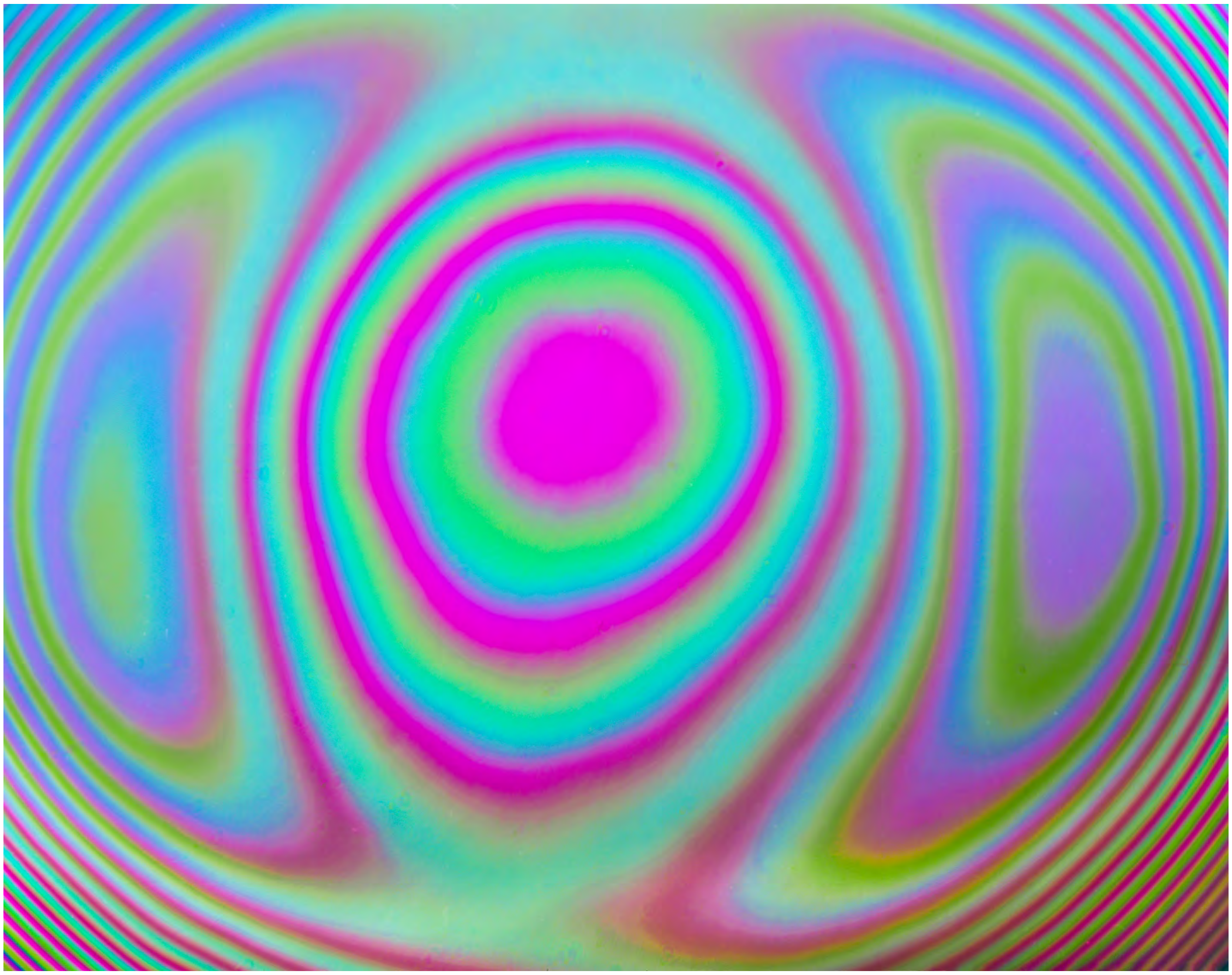


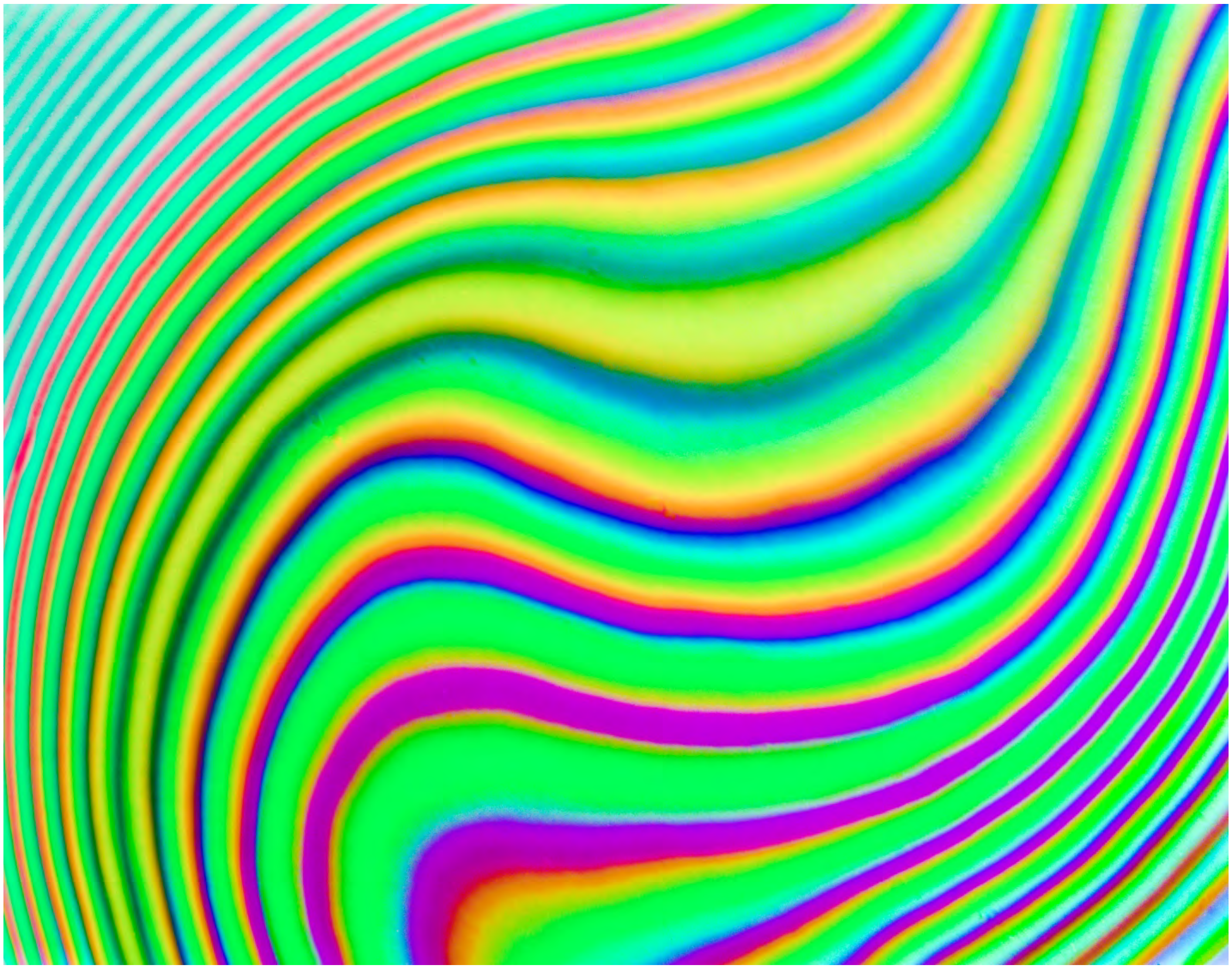


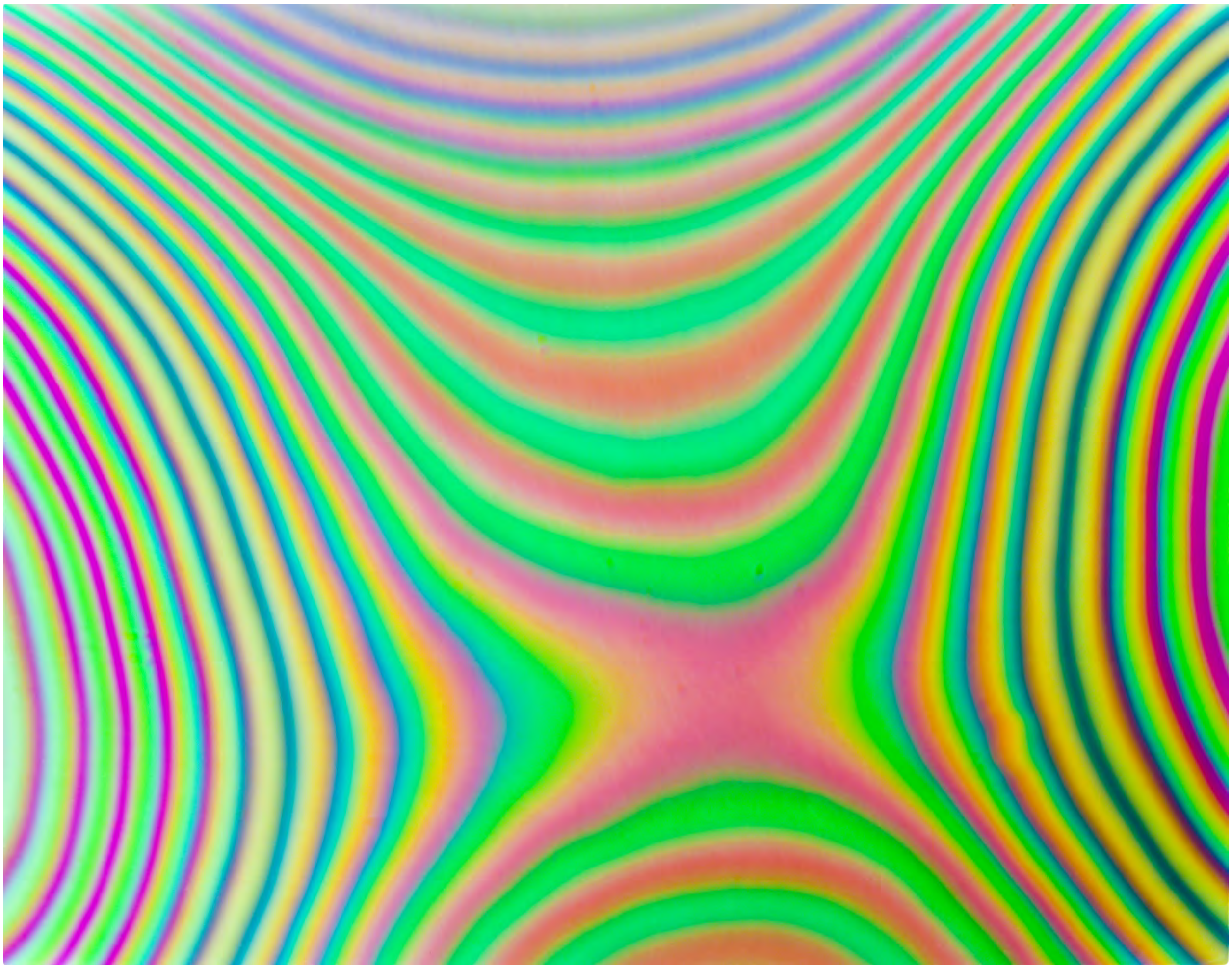


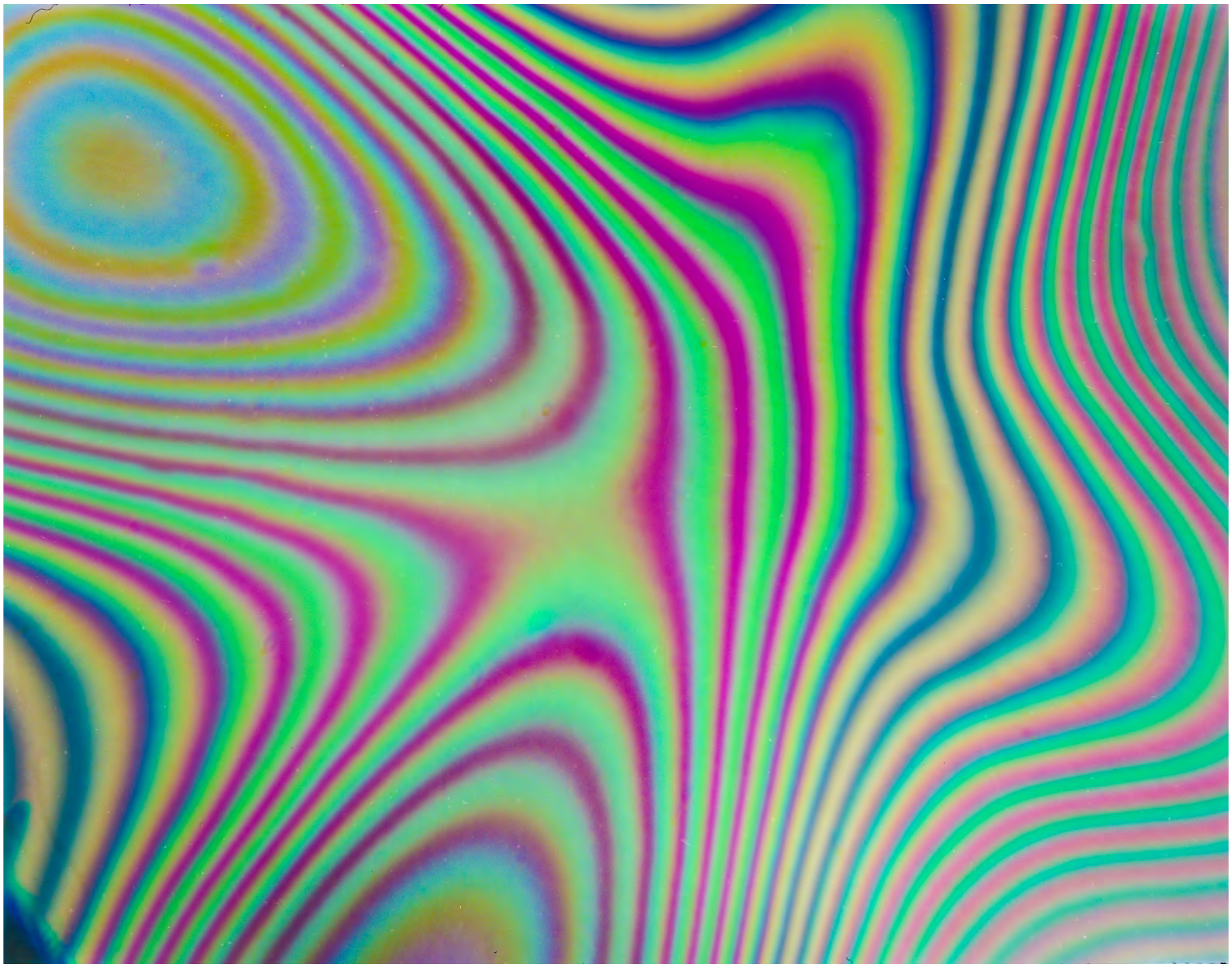












CHAPTER 5 – Integration and Education

5.1 PRESENTING ART AND OPTICS TOGETHER IN OUTREACH

One of the most impactful ways to educate the next generation in the amazing possibilities inherent in forging connections between diverse disciplines is to present them with ideas utilizing creative, interdisciplinary thoughts, methods, and means. Educational outreach to elementary and secondary schools provides an excellent platform upon which minds can be opened to the possibilities their futures hold through various courses of study. For example, a student might not know they would like to be an astrophysicist until someone shows them what 'cool' things an astrophysicist does. By presenting art and optics together in an outreach demonstration, not only are minds being shown the possibilities within each narrow discipline but also possibilities are being opened so as to encourage a vibrant cross-disciplinary creativity. Too often in current culture creativity is squashed, disciplined, or made unimportant in pursuit of 'pure' academics. However, a person who cannot solve problems has little future. Similarly, society has a bleak outlook if the next generation cannot come up with creative solutions to global and local challenges. A student might not have any proclivity towards any of the subjects being presented, but that stimulation to think outside the box will spill into other areas of their lives.

5.2 WHITE-LIGHT, INTERFEROMETRIC, PHOTOGRAPHY EDUCATIONAL PRESENTATION MODEL

An example of how to integrate the arts and optical sciences in an outreach situation is to utilize the techniques developed by the author for white light, interferometric, darkroom photography. This activity would integratively educate students in optical sciences and darkroom photography, while providing essential kinesthetic experience in the process. Ideally, the schools at which these research techniques would be demonstrated would already have the necessary optics/physics and darkroom photography facilities in residence. This would allow the research to be taught in a near exact way it was performed by the author by using existing equipment. As this would incur little to no cost on the part of the school, it is more likely that instructors and facilitators would be willing to have this special material presented.

In the more likely scenario where the school in question does not have optics and/or darkroom photography capabilities in residence, several alternatives that introduce young minds to the combination of art and optics, specifically photography and interference, are detailed hereafter. From a very young age, most present-day children either have their own or have friends/family with cell phones capable of taking photographs. Additionally, there are very few educational systems completely devoid of modern computer technology. That being said, there is a high likelihood that many if not all contemporary students will have taken a photograph of a computer screen with a cell phone. The resulting images more often than not show moiré interference patterns. It can be explained that two factors contribute to the interference pattern produced. Firstly, the overlapping pixel grids of the computer and phone screens can interfere with each other resulting in moiré patterns in the image. Also, the horizontal refresh scan lines used in both devices can conflict producing the same effect.[45] Using their own cell phones with camera capabilities and either the specific classroom's in room computers or a computer lab, students can see and create white light interference fringes for themselves. They then can be challenged to try different screen colors, different angles for the photographs, put small stresses on the screen to change the fringe pattern, etc. to achieve the photograph of the interferogram they desire. This exercise would innovatively challenge the learners to approach the situation with a problem solving mind set, but the creative and modern technological aspect would make the learning fun.

As the phones and computers for this presentation would be supplied by the students and schools respectively, there would be little to no cost to the school. Additionally, no equipment requiring special safety protocols would be utilized making demonstrations and respective hands-on experimentation time extremely safe.

A similar exercise that would introduce students to white light interference and aberrations include a Newton’s rings effects from the combination of an optical flat with a convex lens, interference effects derived from stacked transparent glass or plastic plates, and interference effects derived from oil film-water and soap film interfaces. The presenter’s demonstration/experimentation kit would be comprised of multiple pieces of flat, curved, and irregularly shaped plastic or glass surfaces and together with cooking oil, aqueous soap solutions, and suitable pans and holders to create thin film to create thin film interfaces. Using the classroom’s build in lighting as the source, students would then experiment with the various interference techniques described above to produce aesthetically pleasing fringe compositions. Photographs of the interference effects thus produced – i.e., artistic compositions using white-light interference as the chosen medium – are then taken using traditional film cameras, modern smart phone CCD cameras, or any other CCD cameras (point-and-shoot, DSLR, etc.). This option is ideal for seeing and manipulating the fringe effects physically to create art in a mostly technology-free activity. The photographs of the student’s interference-based art work can then be either printed via traditional dark room technology or digitally rendered for showcase.

Regardless of which of these options is chosen, all presentation alternatives will present students with an interactive learning experience designed to promote interdisciplinary thought and artistic creativity. It is not expected that all students will have natural proclivity to effectively employ this type of blended creativity throughout their futures. However, by encouraging out-of-the-box thinking and creativity through visually stimulating, hands-on activities, the new generation as a whole will be better equipped to creatively handle and solve new worldwide issues as they arise.

CHAPTER 6 – Concluding Remarks

6.1 IMPORTANCE AND IMPACT

This research speaks importance into both in the independent fields of optics and art and their combination. In the field of optical sciences this research has bearing because while imaging primary aberrations was the original goal, new and never before seen aberrations resulted. Additionally, the innovative creative research approach documented herein can be applied to many different avenues of current research in optics and also other fields. In the arts this research brings a brand new creative approach and thought process to the field of photography, while concurrently showcasing the extreme technical background to much modern artistry. Thus, it can be seen that this research has weight in the independent disciplines of optical sciences and fine art photography.

However, not only for the advancement of the photographic art form (in which the combination of art and optics is obviously significant), their union in modern societal thought and practice is of upmost importance. Many careers now require interdisciplinary capabilities or experience. Furthermore, as stated previously, those equipped to think and create using both the artistic and scientific sides of their brains will be more capable of confronting and innovatively solving new collective challenges as they arise in the future. This research aims to encourage further experimentation into heretofore untapped ways to combine art and optics, especially by providing a platform upon which interdisciplinary ideas are presented to others. While the end goal of this research was distinctly artistic, both artistic and scientific aspects were crucial. At almost any point, a more traditionally 'scientific' end goal could have been pursued using the same initial research paradigm. Possibilities include but are not limited to effects of vibrations or air currents on highly sensitive optical systems or tolerances of optical path differences in the white light interferometer. The results could have also been analyzed cinematographically to provide an interesting conversation about the changes in the wavefront over a few μm of path length as well as because the rotation through the white-light fringes is visually fascinating. Through this research, it is hoped that ideas of what comprises modern science and modern art are broadened.

6.2 CONCLUSION

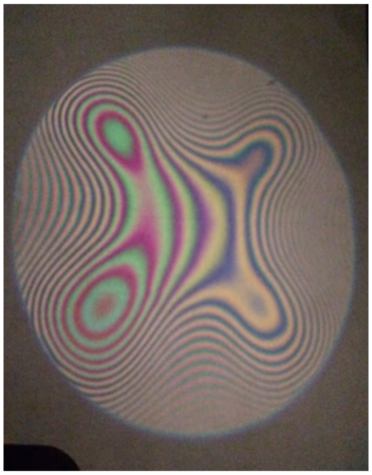
From beginning to end this research was inspired by the idea of combining art and optics. Equipment and instruments were created specifically to achieve the blended discipline results desired, culminating in a formal body of optically generated, aberration-based photographic work by the author. With the success of this research, the framework for a progressive, interdisciplinary art-optics presentation was created. From this fruitful partnership between the arts and sciences, encouraged and brought to light by work such as this, society will be better equipped to step into the next era. With a little change of perspective, that which was once undesirable (such as aberrations) can become a desired and sought after artistic result.

BIBLIOGRAPHY

[1] "EPSRC Science Photo Competition 2016." EPSRC – Engineering and Physical Sciences Research Council. Accessed November 28, 2016. https://www.epsrc.ac.uk/newsevents/events/photocomp2016/
[2] "Stem to Steam." Accessed November 16, 2016. http://stemtosteam.org/
[3] Walter, Chip. "The First Artists." *National Geographic.* Vol 227, no. 1. 2015: 32-57.
[4] Janson, H. W., and Anthony F. Janson. "From Hunting to Husbandry: The New Stone Age." In *History of Art,* 31-33. New York City, New York: Harry N. Abrams, Inc, 1986.
[5] Lindberg, David C. "The Background: Ancient Theories of Vision." In *Theories of Vision From Al-Kindi to Kepler,* 1,13. Chicago, IL: University of Chicago Press, 1976.
[6] Kemp, Martin. *The Science of Optics: Optical themes in western art from Brunelleschi to Seurat*. London: Yale University Press, 1990: 165.
[7] Ibid: 167.
[8] Ibid: 190.
[9] Ibid: 189.
[10] Hockney, David. *Secret Knowledge: Rediscovering the Lost Techniques of the Old Masters.* New York: Penguin Group, 2001: 33-50.
[11] Ibid: 58.
[12] Hockney, David and Charles M. Falco. "Optical Insights into Renaissance Art". *Optics and Photonics News Vol. 11(7),* 2000: 52-59.
[13] Hockney, David. *Secret Knowledge: Rediscovering the Lost Techniques of the Old Masters.* New York: Penguin Group, 2001: 184.
[14] Hirsch, Robert. Seizing the Light: A Social History of Photography. New York: McGraw Hill, 2009: 4-12.
[15] Kemp, Martin. *The Science of Optics: Optical themes in western art from Brunelleschi to Seurat*. London: Yale University Press, 1990: 191.
[16] "Quixotic Fusion: Dancing with Light." TED2012. *TED: Ideas Worth Spreading.* https://www.ted.com/talks/quixotic_fusion_dancing_with_light#t-164381 Accessed December 14, 2016.
[17] Knapp, Stephen. *Lightpaintings*. http://www.lightpaintings.com/ Accessed December 19, 2016.
[18] Storms, Jack. "Biography." http://jackstorms.com/#section-biography Accessed December 19, 2016.
[19] Meyer, Lyndsay. "Art and Optics Converge to Preserve Frescos: Reflected Infrared Light Unlocks New Details of Renaissance Paintings." *OSA The Optical Society.* http://www.osa.org/en-us/art-and-optics-converge-frescos/ Accessed April 03, 2017.
[20] Jenkins, Frances A., and Harvey Elliott White. *Fundamentals of Optics.* New York: McGraw-Hill, 1957: 130.
[21] Hecht, Eugene. *Optics, 2nd Ed*. Reading, MA: Addison-Wesley Publishing Company, Inc, 1987: 220.
[22] Ibid: 70.
[23] Sasián, José. *Introduction to Aberrations in Optical Imaging Systems*. New York: Cambridge University Press, 2013: 69.
[24] Ibid: 69.

[25] Wyant, James C. and Katherine Creath. *Basic Wavefront Aberration Theory for Optical Metrology*. Academic Press, Inc., 1992: 29. Accessed January 28, 2017. https://wp.optics.arizona.edu/jcwyant/wp-content/uploads/sites/13/2016/08/Zernikes.pdf
[26] Ibid: 30.
[27] Ibid: 30.
[28] Anamorphosis. Dictionary.com. *Online Etymology Dictionary*. Douglas Harper, Historian. http://www.dictionary.com/browse/anamorphosis. Accessed: April 4, 2017.
[29] Hockney, David. *Secret Knowledge: Rediscovering the Lost Techniques of the Old Masters.* New York: Penguin Group, 2001: 56-57.
[30] Kemp, Martin. *The Science of Optics: Optical themes in western art from Brunelleschi to Seurat*. London: Yale University Press, 1990: 194-196.
[31] Hockney, David and Charles M. Falco. “Optical Insights into Renaissance Art”. *Optics and Photonics News Vol. 11(7)*, 2000: 52-59. https://www.osapublishing.org/opn/abstract.cfm?uri=OPN-11-7-52. Accessed April 16, 2017.
[32] Hockney, David. *Secret Knowledge: Rediscovering the Lost Techniques of the Old Masters.* New York: Penguin Group, 2001: 185.
[33] Interferometry. Dictoniary.com. *Online Etymology Dictionary*. Douglas Harper, Historian. http://www.dictionary.com/browse/interferometry. Accessed: June 08, 2016.
[34] Jenkins, Frances A., and Harvey Elliott White. *Fundamentals of Optics.* New York: McGraw-Hill, 1957: 399-401
[35] Jenkins, Frances A., and Harvey Elliott White. *Fundamentals of Optics.* New York: McGraw-Hill, 1957: 244
[36] “CHARA:An Overview.” CHARA: An Overview. Accessed June 14, 2016. http://chara.gsu.edu/public/tour-overview.
[37] Malacara, Daniel, ed. *Optical Shop Testing, Third Ed*. Hoboken, NJ: John Wiley & Sons, 2007: 46.
[38] Wyant, James C. “White Light Interferometry.” *Proceedings of SPIE, Vol. 4737* (July 2002): 98-107. Accessed June 29, 2016. http://fp.optics.arizona.edu/jcwyant/pdf/Published_Papers/Optical_Testing/WhiteLightInterferometry.pdf
[39] Bell, Grayson D. and Eldred F. Tubbs. “Use of Grating to Find Interferometer White Light Fringes.” Am. J. Phys. American Journal of Physics, Vol 37, No. 3 (March 1969): 273-275. Doi:10.1119/1.1975504.
[40] Ibid.
[41] Jenkins, Frances A., and Harvey Elliott White. *Fundamentals of Optics.* New York: McGraw-Hill, 1957: 248.
[42] Bell, Grayson D. and Eldred F. Tubbs. “Use of Grating to Find Interferometer White Light Fringes.” Am. J. Phys. American Journal of Physics, Vol 37, No. 3 (March 1969): 273-275. Doi:10.1119/1.1975504
[43] Ibid.
[44] “About the Year of Light.” About the Year of Light. Accessed July 27, 2016. http://www.light2015.org/Home/About.html.
[45] “Moiré Interference Patterns.” Display Mate: The Standard of Excellence for Image and Picture Quality. 2011. Accessed April 13, 2017. http://www.displaymate.com/moire.html

APPENDIX



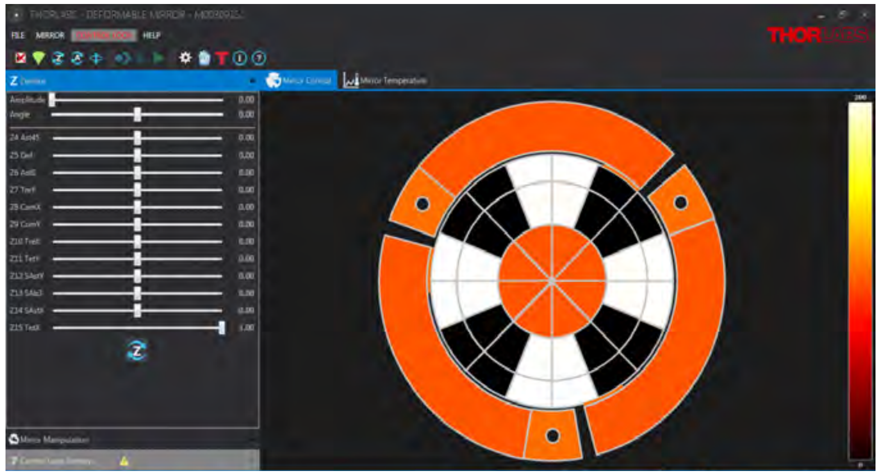
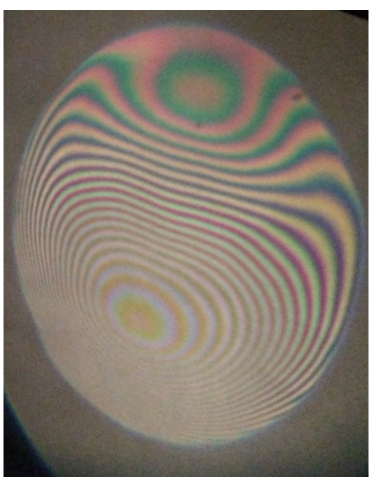


Figure A1 - (Left) Digital image of the tetrafoil (x-axis) aberration (TetX - Zernike Z15 ThorLabs software) as recorded at the time of film exposure.

Figure A2 - (Right) Mirror map showing the contour of the deformable mirror with the amount of tetrafoil aberration present at the time of film exposure. The contour map indicates that all four 'petals' of the tetrafoil should be equal and yet the digital image shows variation. While tilt was not purposely applied to this image, its presence along the y-axis is clear.



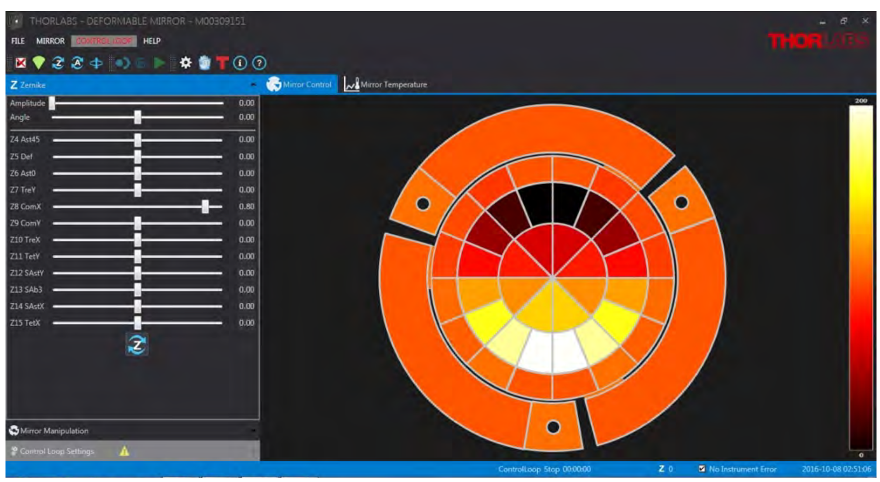
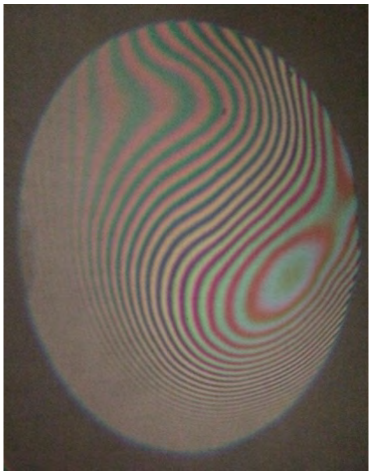


Figure A3 - (Left) Digital image of coma (x-axis) aberration (ComX - Zernike Z8 ThorLabs software) as recorded at the time of film exposure.

Figure A4 - (Right) Mirror map showing the contour of the deformable mirror with the amount of coma aberration present at the time of film exposure.



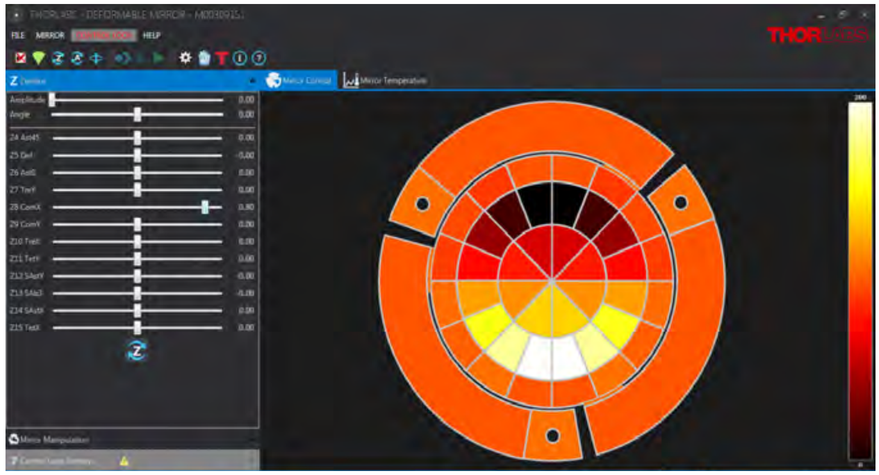


Figure A5 - (Left) Digital image of the third coma (x-axis) aberration (ComX - Zernike Z8 ThorLabs software) with a large and unmeasurable amount of tilt applied as recorded at the time of film exposure.

Figure A6 - (Right) Mirror map showing the contour of the deformable mirror with the amount of coma aberration present at the time of film exposure. As the tilt was applied to the moveable mirror, the mirror map of the deformable mirror remains unchanged from Figure A4 above.

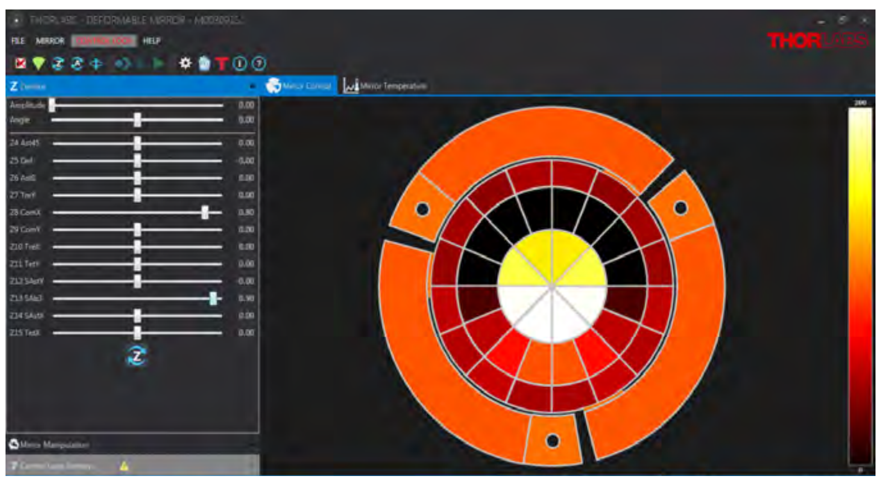
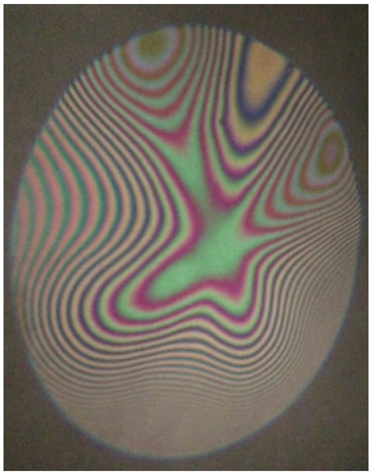


Figure A7 - (Left) Digital image of the first combination of aberrations as recorded at the time of film exposure. Here x-axis coma (ComX - Zernike Z8 ThorLabs software) and spherical aberration (SAb3 - Zernike Z13 ThorLabs software) aberrations were combined.

Figure A8 - (Right) Mirror map showing the contour of the deformable mirror with the amount of coma and aberration present at the time of film exposure.



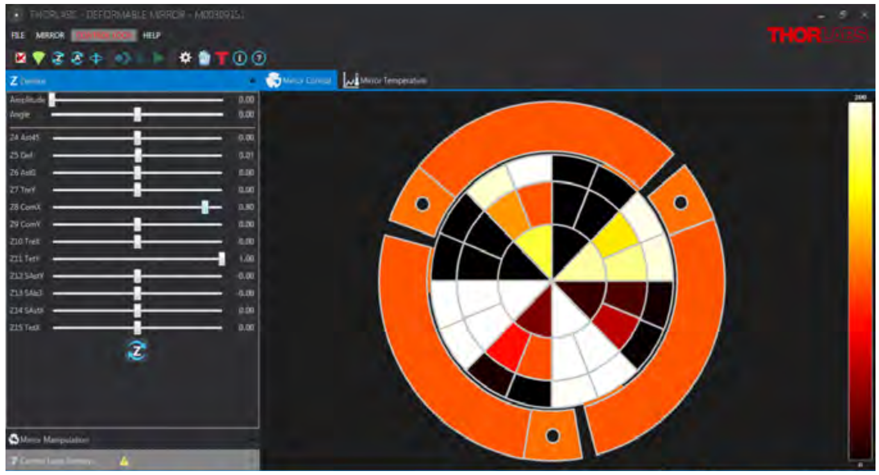


Figure A9 - (Left) Digital image of the second combination of aberrations as recorded at the time of film exposure. Here x-axis coma (ComX - Zernike Z8 ThorLabs software) and y-axis tetrafoil (TetY - Zernike Z11 ThorLabs software) aberrations were combined.

Figure A10 - (Right) Mirror map showing the contour of the deformable mirror with the amount of coma and tetrafoil aberrations present at the time of film exposure.

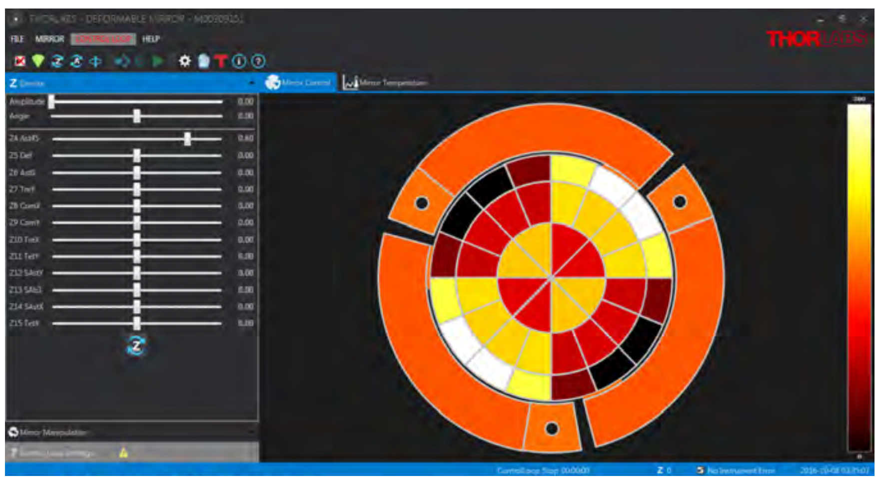
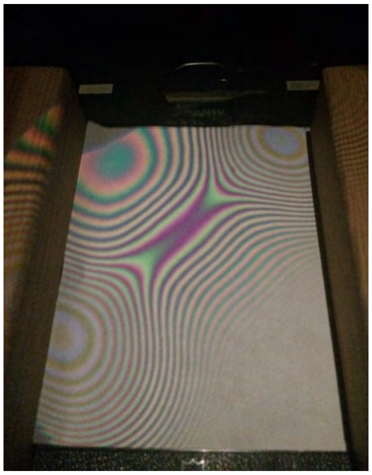


Figure A11 - (Left) Digital image of astigmatism aberration (Ast45 - Zernike Z4 ThorLabs software) as recorded at the time of film exposure.

Figure A12 - (Right) Mirror map showing the contour of the deformable mirror with the amount of astigmatism aberration present at the time of film exposure.



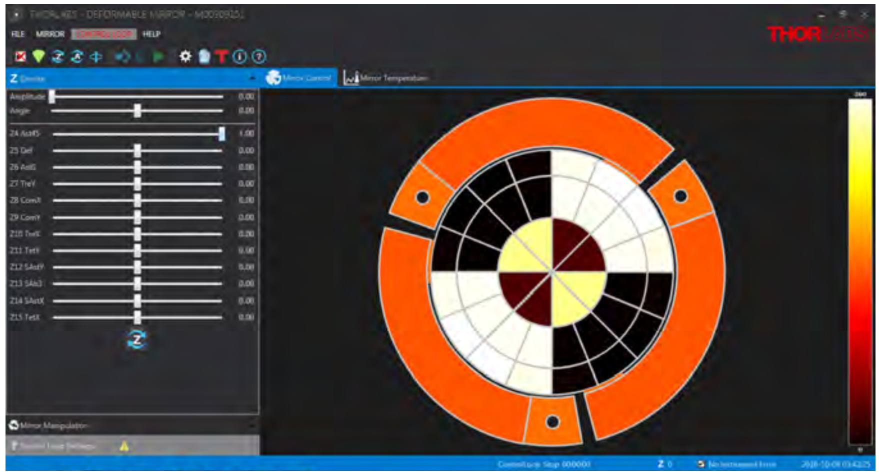
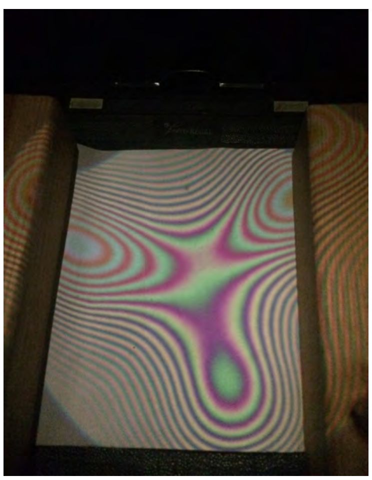


Figure A13 - (Left) Digital image of the second astigmatism aberration (Ast45 - Zernike Z4 ThorLabs software) as recorded at the time of film exposure.

Figure A14 - (Right) Mirror map showing the contour of the deformable mirror with the amount of astigmatism aberration present at the time of film exposure. It can be seen here the amount of astigmatism aberration on the deformable mirror surface is greater than in the previous figures (30 & 31).



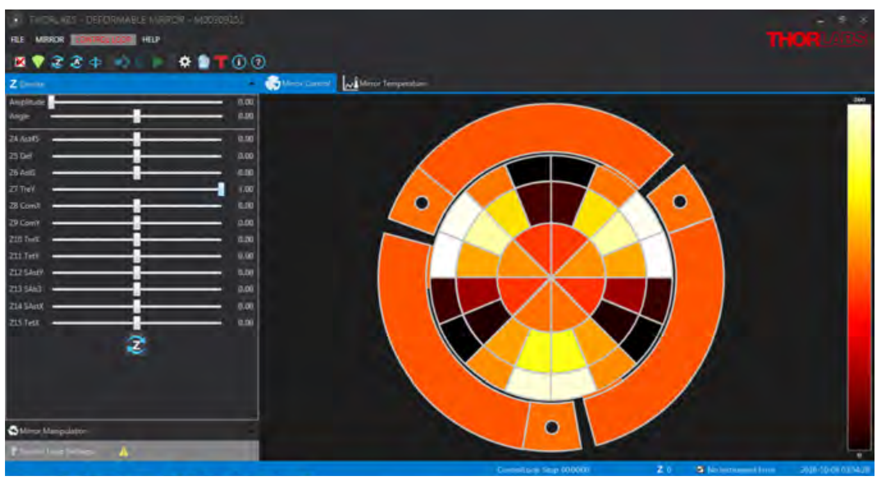
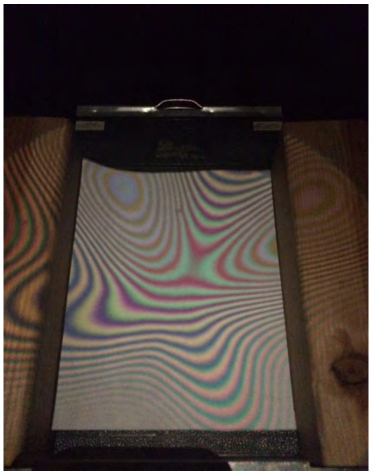


Figure A15 - (Left) Digital image of the trefoil (y-axis) aberration (TreY - Zernike Z7 ThorLabs software) as recorded at the time of film exposure.

Figure A16 - (Right) Mirror map showing the contour of the deformable mirror with the amount of trefoil aberration present at the time of film exposure.



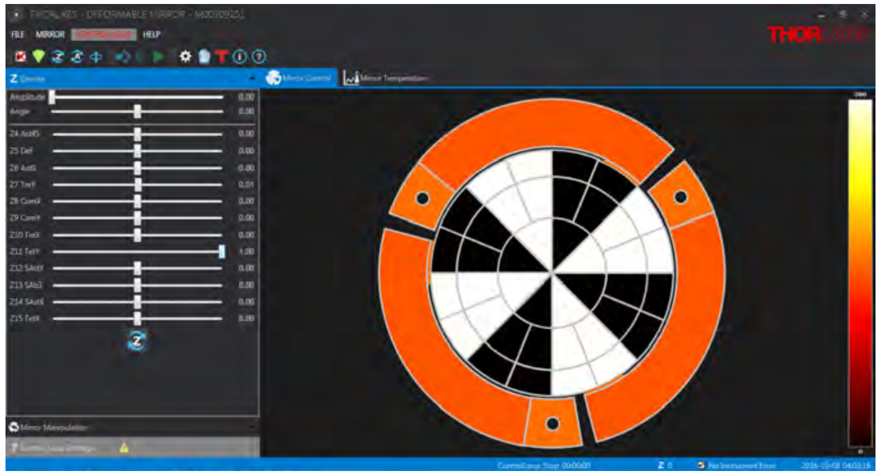
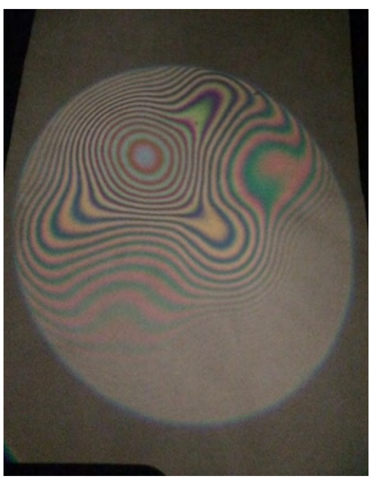


Figure A17 - (Left) Digital image of the tetrafoil (y-axis) aberration (TetY - Zernike Z11 ThorLabs software) as recorded at the time of film exposure.

Figure A18 - (Right) Mirror map showing the contour of the deformable mirror with the amount of tetrafoil aberration present at the time of film exposure.



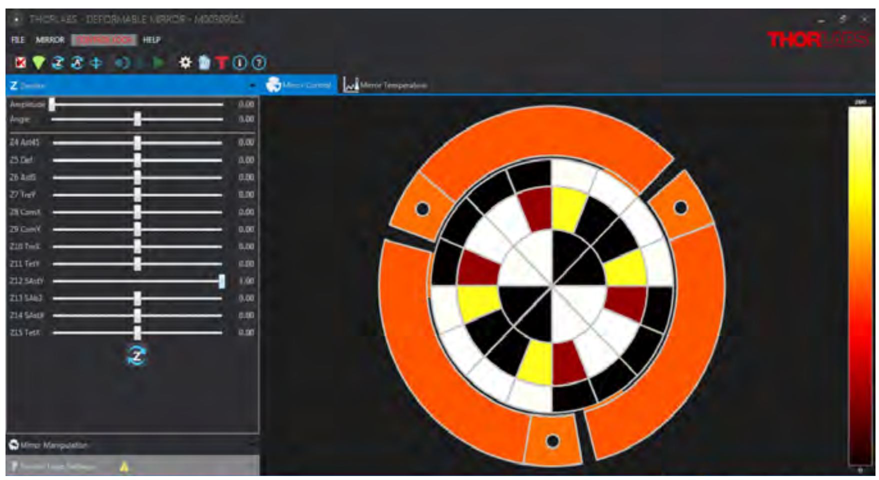
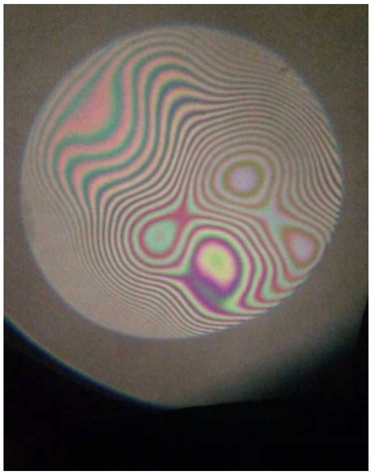


Figure A19 - (Left) Digital image of the secondary astigmatism (y-axis) aberration (SAstY - Zernike Z12 ThorLabs software) as recorded at the time of film exposure.

Figure A20 - (Right) Mirror map showing the contour of the deformable mirror with the amount of secondary astigmatism aberration present at the time of film exposure.



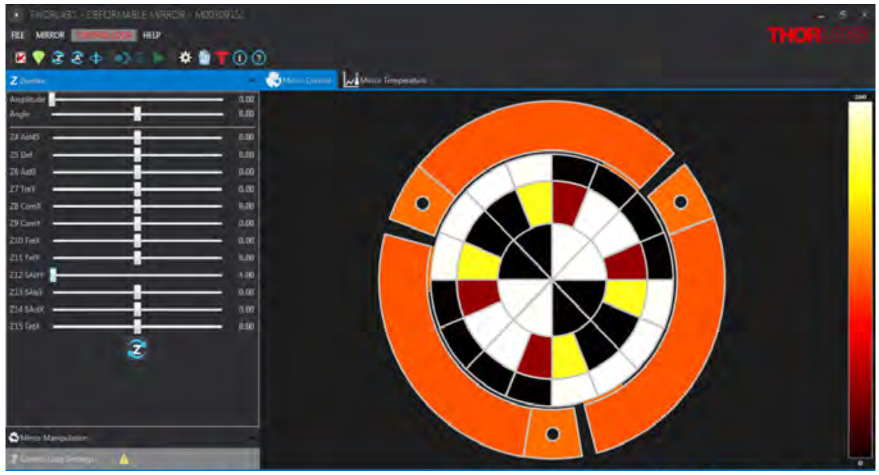
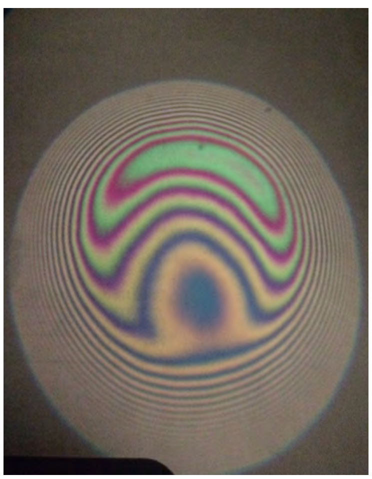


Figure A21 - (Left) Digital image of the second secondary astigmatism (y-axis) aberration (SAstY - Zernike Z12 ThorLabs software) as recorded at the time of film exposure.

Figure A22 - (Right) Mirror map showing the contour of the deformable mirror with the amount of secondary astigmatism aberration present at the time of film exposure.



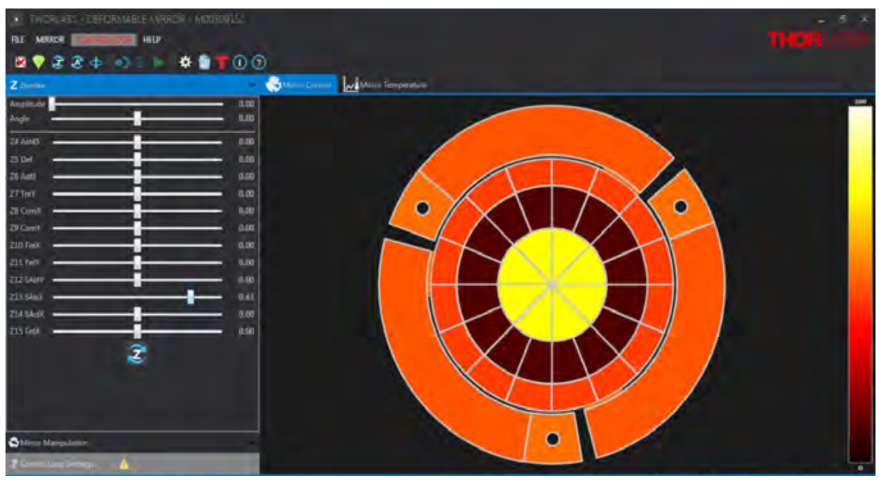


Figure A23 - (Left) Digital image of the primary spherical aberration (SAb3 - Zernike Z13 ThorLabs software) as recorded at the time of film exposure.

Figure A24 - (Right) Mirror map showing the contour of the deformable mirror with the amount of primary spherical aberration present at the time of film exposure.

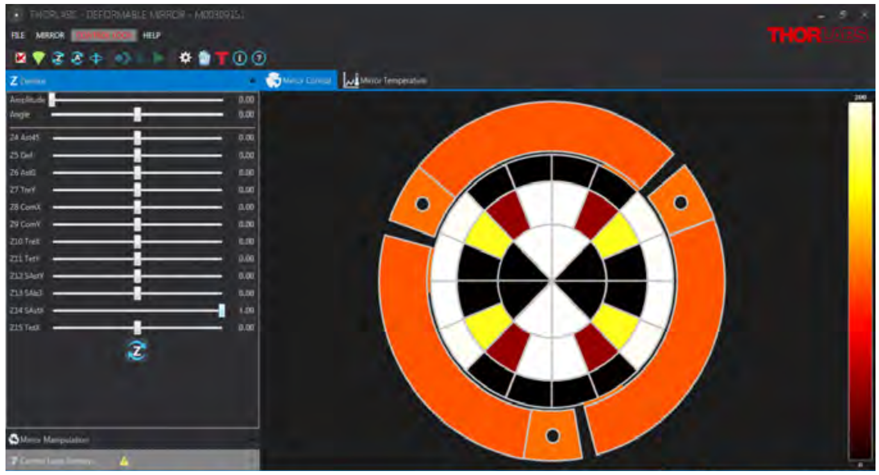
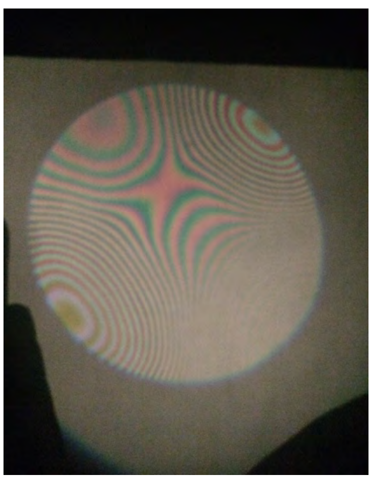


Figure A25 - (Left) Digital image of the secondary astigmatism (x-axis) aberration (SAstX - Zernike Z14 ThorLabs software) as recorded at the time of film exposure.

Figure A26 - (Right) Mirror map showing the contour of the deformable mirror with the amount of secondary astigmatism aberration present at the time of film exposure.



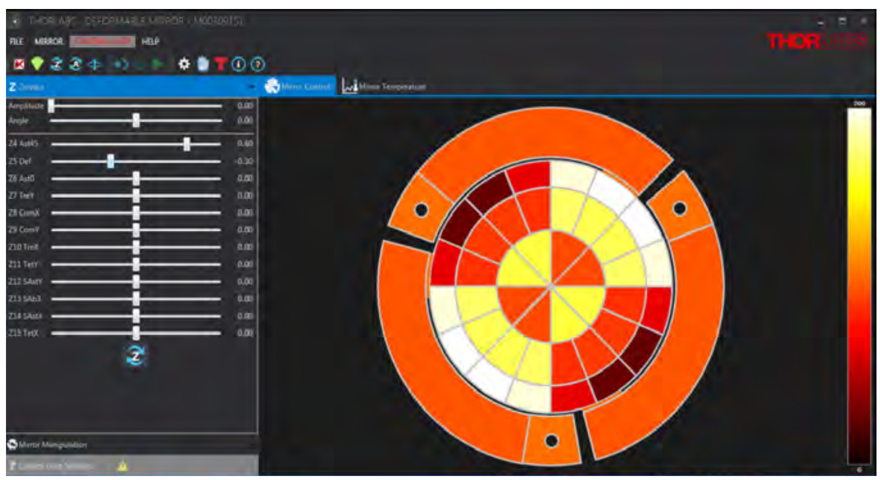


Figure A27 - (Left) Digital image of combination of 45˚ astigmatism aberration (Ast45 - Zernike Z4 ThorLabs software) and defocus (Def - Zernike Z5 ThorLabs software) as recorded at the time of film exposure.

Figure A28 - (Right) Mirror map showing the contour of the deformable mirror with the amount of astigmatism and defocus present at the time of film exposure.

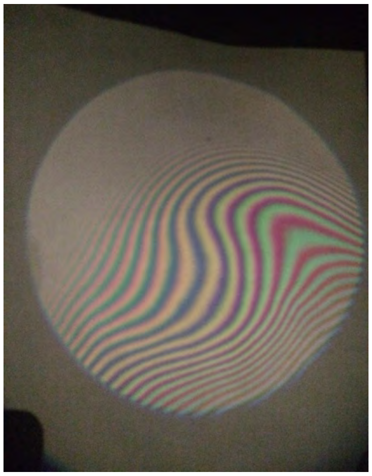


Figure A29 - (Left) Digital image of combination of coma (x-axis) aberration (ComX - Zernike Z8 ThorLabs software) and measurable tip and tilt as recorded at the time of film exposure.

Figure A30 - (Right) Mirror map showing the contour of the deformable mirror with the amount of coma, tip, and tilt present at the time of film exposure.