James C. Wyant: optical disciple, educator, physician, producer

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ABSTRACT

This author's unique personal perspective will honor through examples and analysis the contributions that "Disciple" Wyant has made to the optical sciences and metrology discipline and for the people that work within it. In spring 1974 the author was at the Optical Sciences Center (OSC) as a graduate student when "Physician" Wyant interviewed and made a diagnosis and improvement to a holographic interferometry configuration of a project the author was working on. "Student" Brooks went on to became one of the first of Dr. Wyant's future graduate students. He also enrolled in "Educator" Wyant's first Optical Testing OPTI213 class in 1975 where optical metrology and wavefront characterization of electromagnetic radiation was presented, defined and clarified to make the field addictive and irresistible to the author. It would prove to be the author's strongest career influence for the next 35 years, pointing him to a profession in optical metrology within aerospace laser industrial design, integration and test engineering functions. This presentation will illustrate derivative effects of "Producer" Wyant's contributions, including examples associated with the presenter's industry experience. Also presented are examples of James Wyant's generous philanthropic campaign.

Keywords: Optical testing, optical metrology, wavefront testing, wavefront sensors, adaptive optics, phase shifting interferometry, electromagnetic radiation history

1. INTRODUCTION

This manuscript will articulate with the aid of some personal and other selected examples how Dr. James C. Wyant has not only been a master in the modern photonics craft of optical science and engineering and has influenced the direction of optical metrology in particular, but also positively influenced the author's career and undoubtedly that of others. The author first met Wyant in 1974 during his visit to the Optical Sciences Center (OSC), University of Arizona, where only a year earlier the author had started the Master's Degree program. Wyant became the author's Thesis Advisor and there were intermittent professional interactions over the subsequent decades. Therefore, this document will not attempt to provide an exhaustive comprehensive coverage of the Wyant career from personal examples alone.

Where possible, examples of this author's work are used to illustrate particular points and influences, and that is often the source of the uniqueness of this perspective. But an apology is made in advance as the author is not the focus of this document. Also, unfortunately there are not a lot of technical details on some personal industrial diagnostic projects either because of the sensitivity of the work, or publications were never created, or the details were not deemed relevant. The purpose is to focus on the role of James Wyant in the development of modern optical testing and metrology, optical sciences education, and upon his students.

In an early call for papers for this session in 2020, I recalled reading something that referred generally to the major contributions James Wyant made to our "craft," which I will interpret to mean photonics but not necessarily exclusively so. There appears to general agreement but some variation in the definition of photonics. One vendor uses the phrase[1] that photonics is "the science of generating, detecting and manipulating light." That same vendor's catalog in 2008/2009 subtitled it with[2] "Solutions to Make, Manage, Measure light." Wikipedia has its own version[3] with, "Photonics is the physical science and application of light (photon) generation, detection, and manipulation through emission, transmission, modulation, signal processing, switching, amplification, and sensing**."** A pre-photonics era terminology phrase usage applicable to "craft" comes from the description in the 1972 Optical Sciences Center's "Program of Study" description at the University of Arizona, two years before Jim Wyant arrived to teach at that institution. The opening paragraph began (italics added), "Optics is an area of rapid current growth both in its *basic scientific formulations* and in its *applications* in a wide *variety of technical fields*. Phenomena of interest are those related to the *generation, propagation, imaging, or detection of electromagnetic radiation* from the vacuum-ultraviolet to the far-infrared region of the spectrum." For the purpose of this manuscript, I shall be referring to the photonics "craft" as "the science and engineering of the generation, control, and/or detection of electromagnetic radiation in the ultraviolet, visible and infrared bands." But for perspective, the photonics industry is also part of a larger ongoing industrial revolution.

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Within that craft most of the emphasis herein will be on optical testing and metrology where James Wyant has chosen to make most of his industry contributions. And there especially he has become a leader, promoter and example, particularly by exploiting the revolutionary technique of "phase shifting interferometry" technology and computation for the measurement of optical path phase differences across interfering wavefronts. In 1991 he wrote[4], "The art of testing optical components has become a science with the introduction of new lasers, solid-state detector arrays, microprocessors, and sophisticated software. . . The major development in interferometric optical testing in the 1980's was the marriage of electronics, microprocessors, and interferometers for rapid acquisition and analysis of interferometric data. . . Several commercial phase-shifting interferometers for measuring surface shape and surface roughness were introduced during this time. . . Phase-shifting interferometers made it possible to obtain interferometric test results quickly and accurately – an improvement over the older method of looking at an interferogram to determine how the fringes departed from being straight and equally spaced."

Because electromagnetic radiation is so central to discussion of this "craft," and because last year was the 200th anniversary of the discovery of electromagnetism by Hans Christian Oersted[5], Section 2 will briefly review that period of science long ago that preceded Jim Wyant's career. Section 2 is a synopsis from the author's Shack Tribute slide presentation of 2020[5].

Subsequently James Wyant is presented sequentially as a Disciple, Educator, Physician, and Producer (implicitly a leader) in Sections 3, 4, 5, and 6 respectively. These should not be construed as an orthogonal basis set because they are not "linearly independent" in this manuscript. Therefore, there is some overlap that will appear in Sections 3-6 below.

The Summary, Conclusions and Parting Remarks conclude in Sections 7-9.

2. LOOKING BACK AT THE DISCOVERY OF ELECTROMAGNETISM AND ELECTROMAGNETIC RADIATION

The scope of optical science and engineering includes not only classical but more importantly modern optics generously integrated with evolving development of computers and lasers. But it is always associated with electromagnetic radiation. Of this phenomena Einstein is quoted as saying,[6] "For the rest of my life, I will reflect on what light is." Additionally, "not only our communications but also almost our whole way of life has come to depend on technology that exploits the electromagnetic field-a feature of the physical world that was undreamed of until it was first envisaged by Faraday, then elucidated by Maxwell."[7]

Despite the association between electricity and magnetism "had been recognized by investigators for many decades,"[8] and the invention of the voltaic pile "battery" by Alessandro Volta in 1800 enabled convenient subsequent laboratory experiments with electricity, the discovery and beginning of electromagnetism is now taken to have begun in the spring of 1820 in Copenhagen, Denmark. One evening during his public science lecture and demonstration, Hans Christian Oersted noticed a slight deflection of his compass needle when a current was passed through a nearby wire. On 21 July 1820 Oersted first published his short report of the account (reportedly 3 months after[9] the experiment) in Latin ("Experimenta circa effectum conflictus electri in acum magneticam") describing his version of the event and the connection between electricity and magnetism. Due to some conflicting reports, there was confusion, ambiguity and skepticism for decades. This was despite eight months after the event "Faraday wrote a historical survey of the evolution of electromagnetism up to April 1821. . . He acknowledges Oersted's discovery to be not only a lucky chance but also the fruit of a deliberate search[10]." And that is the general consensus today.

Following Oersted's July 1820 report, word spread fast. On 11 September Andre-Marie Ampere at the Ecole Polytechnique in Paris heard his friend Francios Arago announce that Professor de la Rive had repeated the Oersted Experiment in Geneva. Ampere quickly acted, and following days of rapid calculations and experiment Ampere presented a mathematical analysis of Oersted's experiment and extended understanding with the first of several papers on electrodynamics[7]. His work eventually included the analysis and experiments with "solenoids" (even providing the name) and galvanometers, and for this extensive work in this short period he is now remembered as the founder of electromagnetism. In 1861 Maxwell would write the equation relating a magnetic field to the current for Oersted's experiment and name it "Ampere's Law."

British scientist Michael Faraday subsequently learned of Oersted's discovery in October 1820 at the Royal Institution, where he and mentor Humphry Davy repeated the experiment. Following unrelated intense work and personal distraction (marriage), Faraday returned to electromagnetism when asked to write a historical review article for the

Annuals of Philosophy, "Historical Sketch of Electromagnetism." He then developed his own views which he applied to experiment and in 1821 demonstrated electromagnetic motor action. The rest of his decade was spent with career advancement and patriotic service with optical glass development. But reportedly[11] Faraday's "mind kept revolving on Oersted's discovery, and his interest was further excited by the continuing revelations of electromagnetic effects being reported from abroad. . . He reasoned that if electricity could produce magnetism, as in the Oersted experiment, why not the converse? Could not magnetism produce electricity?"

Late in 1831, Faraday focused his energy and demonstrated the first electromagnetic induction and then the generation of electric current continuously by rotation of a conductor in a magnetic field. Demonstrating the principles of the electromagnetic generator would eventually prove to revolutionize the world with a power source. But the future equation describing the induction effect would be a key ingredient Maxwell would need for his modeling of electromagnetic waves. In 1857 Faraday and Maxwell began collaborating: after years of experimental accomplishments and 10 years before his death, Faraday had found someone to continue with his field concepts mathematically.

Maxwell's paper "A Dynamical Theory of the Electromagnetic Field" (read aloud in 1864, published in 1865) included the following statements regarding light as being electromagnetic radiation:

"The mathematical form of the disturbance therefore agrees with that of the disturbance which constitutes light, being transverse in the direction of propagation."

"The agreement of the results [velocity calculation] seems to show that light and magnetism are affections of the same substance, and that light is an electromagnetic disturbance propagated through the field according to electromagnetic laws."

Maxwell died young of cancer at 48 in 1879, still revising his Treatise. His legacy of electromagnetic wave theory was at risk but 4 Maxwellians stepped into the vacuum: Francis Fitzgerald and Oliver Lodge who tended to work together; and Oliver Heaviside and Heinrich Hertz who tended to work separately. As a group they were the successor disciples of Maxwell, and they "transformed the rich but confusing raw material of the Treatise into a solid concise, and well-confirmed theory."[12]

Although the FitzGerald-Lodge collaboration first conceived of electromagnetism-based generation mechanisms, they had no detection scheme. Oliver Heaviside rewrote Maxwell's original equations into the shorter form familiar today, using vector calculus which he had helped invent. Hertz independently reformulated Maxwell's equations into a form very similar to that of Heaviside. He then conducted the crucial experiment of generation and detection of electromagnetic radio waves in 1887-1888. The Hertz experiment convinced the community of the existence of the predicted waves; that Maxwell's theory was correct; and by association with the measurement of the velocity being the same as light, that Maxwell was also correct in that light is electromagnetic radiation.

"What had captivated Hertz and set him on his quest was a beguiling but strange scientific idea - the brainchild of British experimentalist Michael Faraday . . . that had been raised into a full mathematical theory by the young Scot James Clerk Maxwell three decades later . . . that space itself acted as a repository of energy and a transmitter of forces: it was home to something that pervades the physical world yet was inexplicable in Newtonian terms - the electromagnetic field."[13]

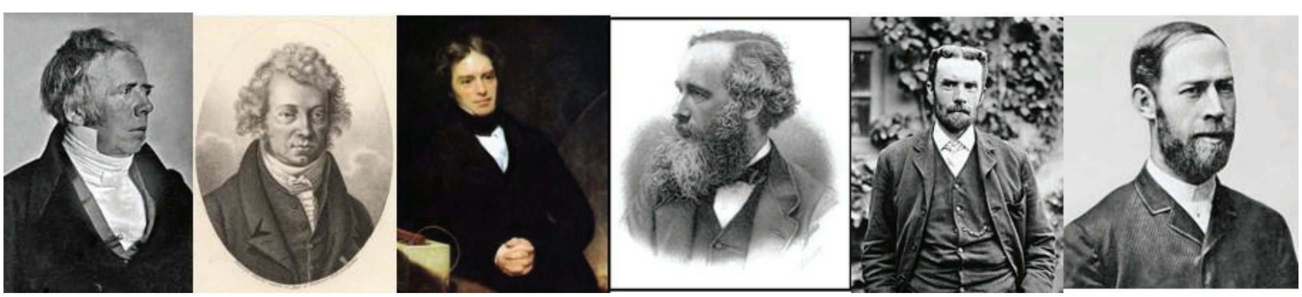

Figure 1 Electromagnetism Founders (L-R): Oersted, Ampere, Faraday, Maxwell, Heaviside, Hertz

Issac Newton said, "If I have seen further, it is by standing on the shoulders of giants." Modern photonic workers stand on the shoulders of these pioneer scientists. Jim Wyant carries on for others now the same dedication and intensity of commitment to scientific progress expressed by the "founders" of electromagnetic radiation discovery that paved the way for him, and he has become a giant himself through his actions and products for his successors.

3. OPTICAL DISCIPLE

3.1 Discipleship Model

One definition of "disciple" is[14] "one who accepts and assists in *spreading* the doctrines of another: as . . . a convinced adherent of a *school* or *individual*." (italics and underline added). But to become a disciple, what was the inspirational doctrinal source here? It reportedly[15] appeared to be a closely spaced series of positive reinforcing events between the end of his junior year in college and after the start of his senior year. Jim Wyant became a "convinced adherent" of the school of optics ("hooked" in his words) during his college years through a series of events including the following: the creation of a successful light scatter sensor development for summer employer Libby-Owens-Ford Company; a subsequent introduction to the 3rd edition of Principles of Optics by Francis A. Jenkins and Harvey E. White; followed by exposure to his first laser and hologram. Subsequent association with Robert Shannon at Itek Corporation probably contributed with the "individual" part of discipleship.

The resultant resonance was enough to apparently launch him, but he made it dovetail with an aspiration since childhood.to become three types of persons: a researcher, an inventor, and to start and run a business.[15] Also, as the author's Master's Thesis advisor, he once said he had an action plan: to work in industry, transfer to academia and then to business and back and forth, or something to that effect.

3.2 Dedication to a craft

After considering several definitions of the English word "craft," the following working definition seems an appropriate amalgamation from numerous definition sources: "a trade or activity that requires skill, experience, and sometimes innate talent, that results in a product (or products) of value." To be successful in any craft, in this case photonics or the smaller specialty field of optical metrology, one needs to be disciplined in a quest for truth in addition to having personal attributes and experiences required by the craft. If one then not only expresses intense devotion to a craft but also commitments and sacrifices, as Jim Wyant has by philanthropically donating millions of dollars into the Optical Sciences Center to promote his cause to the world while making it part of his life, that doesn't sound like mere career or ambition. It appears more like committed discipleship work.

Execution of this recipe has already produced this functioning giant in our "craft." But given the announced vision at the 2019 formal opening ceremony of the Wyant College of Optical Sciences, most anticipate even more progress from the synergy expected from the inclusive integration of various additional disciplines via endowed chairs to the College.

Also consistent with discipleship, he has publicized, inspired, promoted and guided numerous successor disciples, some who strive to emulate his example of enthusiasm, commitment and energy. Examples follow in the next three sections.

4. OPTICAL EDUCATOR

4.1 Optical Testing classes: spreading the "word"

The second type of person model for Professor James Wyant is "Educator." His formal educator career[16] began in 1969 at the Lowell Technological Institute: fist as lecturer of physics then as instructor of mathematics and physics. After Itek work, teaching continued in 1974 at the University of Arizona as an assistant professor, then associate professor, then professor, then Director of the Optical Sciences Center; subsequently Dean of the Wyant College of Optical Sciences, and now professor emeritus also. This is in addition to professor of Department of Electrical and Computer Engineering. He also had visiting professor roles at the Institute of Optic (Rochester) and Changchun University (China), and was a visiting scientist at the Commonwealth Scientific and Industrial Research Organization (Australia). He has supplemented these roles with prolific professional publications and book involvement to educate our industry. He has also been responsible for advising and graduating 59 graduate students at the Optical Sciences Center.

I was enrolled in the first OSC OPTI213 Wyant Optical Testing class in the fall of 1975 (Dr. Meinel had apparently taught a previous OPTI213 Optical Testing class about 1972-before I arrived to OSC-according to an OSC brochure.) It was in this class that I was first exposed to optical testing immersion and metrology as a field, and I resonated with it. Although I completed this course with the highest overall grade, that was more due to my enthusiasm of the subject than any superior academic credentials. The syllabus for the 1975 fall class is shown below in Figure 2. Sections 5.3 and 5.4 were the heart of the class, as remembered by this former student, but the totality of the techniques provided a well-rounded education for the testing discipline.

J. C. Wyant
Fall, 1975

Optics 213 -- Optical Testing

1.0 Introduction

- 1.1 Theory behind optical testing
- 1.2 Components to be tested
- 1.3 Pertinent measurements

2.0 Qualification of Optical Material

- 2.1 Internal defects
- 2.2 Refractive index 3
- 2.3 Strain 9
- 2.4 Mechanical and thermal properties 10

3.0 Measurement of Paraxial Properties of Optical System 12

- 3.1 Focal length 12
- 3.2 Cardinal points 16
- 3.3 Aperture

4.0 Aberrations

- 4.1 Spherical wavefront, defocus, and lateral shift
- 4.2 Angular, transverse, and longitudinal aberration
- 4.3 Seidel aberrations
- 4.4 Chromatic aberrations

5.0 Component Testing

- 5.1 Flat surfaces
  - 5.1.1 Surface roughness (Polish)
  - 5.1.2 Surface flatness
  - 5.1.3 Surface parallelism
- 5.2 Prism testing
  - 5.2.1 Interferometer
  - 5.2.2 Goniometer
  - 5.2.3 Autocollimator
  - 5.2.4 Visual testing
- 5.3 Curved surfaces and/or lenses
  - 5.3.1 Radius of curvature
  - 5.3.2 Surface figure
    - 5.3.2.1 Test plate
    - 5.3.2.2 Twyman-Green interferometer (LUPI)
    - 5.3.2.3 Multiple beam interferometry (SWIM)
    - 5.3.2.4 Scatterplate interferometer
    - 5.3.2.5 Star test
    - 5.3.2.6 Hartmann test
    - 5.3.2.7 Foucault test
    - 5.3.2.8 Wire test
    - 5.3.2.9 Ronchi test
    - 5.3.2.10 Shearing interferometer
- 5.4 Aspheric surfaces
  - 5.4.1 Null test
    - 5.4.1.1 Refractive null corrector
    - 5.4.1.2 Reflective null corrector
    - 5.4.1.3 Holographic null corrector
  - 5.4.2 Non-Null test
    - 5.4.2.1 Long-wavelength Twyman-Green interferometer
    - 5.4.2.2 Two-wavelength holography
    - 5.4.2.3 Moire
    - 5.4.2.4 Lateral shear interferometer
    - 5.4.2.5 Geometrical tests

6.0 Assembly and alignment of system

- 6.1 Principles of cell design
- 6.2 Centration and tilt of elements
- 6.3 Evaluation after assembly

7.0 System Evaluation

- 7.1 Visual testing
  - 7.1.1 Geometrical tests
  - 7.1.2 Interferometer tests
- 7.2 Photographic test
- 7.3 Image photometry
  - 7.3.1 Veiling glare
  - 7.3.2 Spread function measurement
  - 7.3.3 Encircled energy measurement
  - 7.3.4 Optical Transfer Function measurement

Figure 2. Copy of First Wyant OPTI213 Optical Testing Course Syllabus Fall Semester 1975

A shortened version of Assistant Professor Wyant's Optical Testing course became a regular part of the OSC "Optical Short Course" series of instructional presentations and handout material from several of the OSC staff. My OPTI213 class notes and the Short Course handouts became useful reference tools for working in this area. This was especially helpful before the first edition of Optical Shop Testing by Daniel Malacara was published in 1978. Interestingly, the 1980 syllabus in the Wyant Short Course emphasized interferometry testing at the beginning, and also added the Mach-Zehnder interferometer, which my Master's Thesis and career, and Jim Wyant's career, were associated with.

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Figure 3. Top part of Wyant 1980 Optical Short Course Syllabus

A key part of professor Wyant's curriculum included a 1-unit laboratory numbered OSC213L. It was in this class that we gained familiarity with the often simple but powerful testing tools that I would use later in my career. These included the star testing, shearing interferometry, numerous other interferometry configurations and methods, interferogram analysis and other processes which I would use routinely use and expand upon in creative arrangements for decades. Many of the "Surface Figure" test methods would be adaptable to optical wavefront testing for adaptive optics sensors. The syllabus for the fall 1975 lab is shown in Figure 4 below. (Unfortunately, my 213L laboratory notebook has been misfiled, so the full program, wonderful images and photography cannot be shared within this manuscript.)

J. C. Wyant
Fall 1975

Optics 213L -- Optical Testing Lab

Lab #	Date Finished	Lab
1	Sept. 4	Refractive index-refractometer
2	11	Internal defects
3	18	Prism testing
4	25	Radius of curvature measurement
5	Oct. 2	Twyman-Green interferometer
6	9	Scatterplate interferometer
7	16	Computer analysis of interferograms
8	23	Star test
9	30	Hartmann test
10	Nov. 7	Foucault test
11	13	Wire and Ronchi test
12	20	Shearing interferometer
13	Dec. 1	Alignment techniques

Figure 4. Copy of First Wyant OPTI213L Optical Testing Lab Syllabus Fall Semester 1975

This optical wavefront testing immersion had consequences. It helped lead directly to my first professional career position after my Master's degree in 1976. It was with the Government Products Division of Pratt & Whitney Aircraft (part of United Technologies Corporation-UTC) which was developing the 10.6 micron high-energy gas dynamic laser (GDL) in West Palm Beach, Florida as well as working a contract in adaptive optics systems called HICLAS.

At UTC I specifically became involved in not only characterizing the performance of deformable mirrors for high energy lasers[17] but also in the development of an "image plane chopping" wavefront error sensor[18] (shown in Figure 6B) for modal control of adaptive optic systems. To demonstrate closed loop operation with that sensor, I previously had created an aberration generator[19] for primitive demonstration of sensing and correction. OSC education in general, and from Dr. Wyant in particular, was directly relevant with all of these assignments.

4.2 Advisor and mentoring

The educator is inherently also a mentor to students. Assistant Professor/Advisor Jim Wyant recommended in 1976 that I not take the UTC position at that time, suggesting instead that since I had expressed an interest in applying for the PhD Optical Science program I should stay in Arizona and finish (as my father advised). But the opportunity to do adaptive optics work in Florida was too attractive, and was beneficial. (Dr. Gaskill inaccurately warned, "You will never return!") Unfortunately, by departing I missed some of the beginning of the OSC Phase-Shifting Interferometry "revolution."

After Assistant Professor Jim Wyant began at OSC he replaced Robert Shannon as my advisor. Professor Wyant provided guidance and assistance with my topic of creating and characterizing atmospheric turbulence simulation plates. He found funding for beamsplitters for a needed Mach-Zehnder interferometer for the characterization, but not a spatial filter assembly component needed to remove spatial noise the irradiance profile of the HeNe laser test beam, due to cost. But using the skills learned from the OSC student machine shop operator over my first two years, I built my own spatial filter assembly[20], shown in Figure 5A, even making my own pinholes. Afterwards I thought other OSC projects might be interested, so in the spirit of my entrepreneur advisor I advertised and recruited interested parties. I accepted the machine shop slight modification recommendations, and they produced the black anodized units of Figure 5B. Afterwards I submitted a patent application, but the University declined it based on the recommendation of Dr. Wyant, who had concluded the spatial filter assemblies were an example of good engineering but not patent-worthy inventions. I agreed.

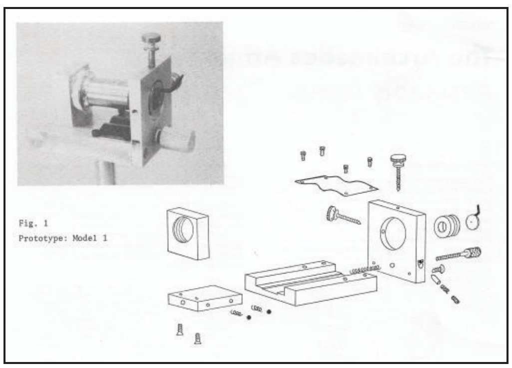

Figure 5A. Prototype Spatial Filter[20]

Figure 5B. Modified prototype production (©Brooks 2021)

The patent lesson was carried forward to UTRC in Florida. There this author optically designed and had built up a brassboard prototype scanning "image plane chopping" wavefront sensor conceived by engineer Dean Cornwell, the inventor. It was created to scan the focal region at three longitudinal positions with multiple three-slit patterns (with each slit in the pattern of three at a different angles) in order to sense beam tilt, focus and astigmatism. After it was built and operating Dean asked me if I wanted to have my name on the patent[21] he was submitting. Even though I had built the first working model, I had no real input on the original design concept. Remembering Professor Wyant's conservative approach to patent assignment, I declined and still feel that was also the correct decision.

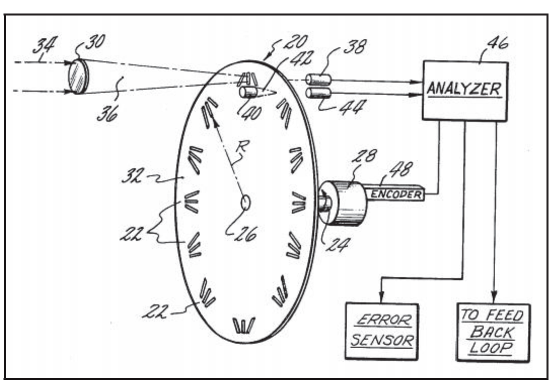

Figure 6A. Patent 4,256,958 Concept[21]

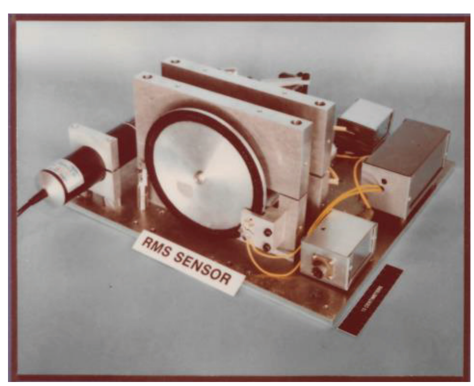

Figure 6B. Brassboard implementation[13]

While working at UTC in Florida, now Professor/Advisor Wyant also enabled me to continue my matriculation at the University of Arizona the spring semester of 1977 by being my advisor on an independent study project. This continuing enrollment not only allowed me to take (and pass) the PhD Qualifying exam that spring, where Professor Wyant participated as part of the Oral Prelim Exam team, but it also opened the door to my subsequent dissertation work.

The topic I worked on for those 2 units of course OPTI299 "Independent Study" was the optimal design for the surface characteristics of the scatterplate element for use in a Scatterplate Interferometer. In October 1978 I presented a paper[22] on that research at the Optical Society Meeting in San Francisco where I displayed a nomograph that related scatter cone and fraction of energy scattered as a function of surface autocorrelation length and variance for different types of power spectral density functions. In the audience of the oral presentation was Professor Wolfe from the OSC who had interest in characterizing surfaces with scatter measurements. In January 1979 he wrote me: "I enjoyed the paper you presented at the Optical Society Meeting entitled 'Scatterplate Design' very much. I would appreciate receiving a reprint of your paper and any other reprints you might have on this subject." Later that year Professor Wolfe became my Dissertation Advisor at the OSC. Thus, Professor Jim Wyant had helped facilitate that opportunity. Thus, I had two optimally complementary advisors at the OSC: Jim Wyant for the Master's degree, and Bill Wolfe for my Ph.D. dissertation. That combination would serve me well throughout my career in wavefront metrology, and scatter metrology in the infrared (IR), respectively. The IR and scattering inculcation at the OSC Annex became added value: most of the interferometers I developed later were for the IR, and scatter education helped troubleshooting skills during integration testing.

4.3 Subsequent assignments that the Optical Testing class education prepared me for

The UTC professional experience of 76-79, coupled with the prior optical education of 73-76 and completion of OSC work in 79-81, opened the door to a subsequent position for me at the Air Force Weapons Laboratory ("AFWL," now part of Phillips Laboratory) with Rocketdyne Division of Rockwell International in 1982. I was originally transferred from Rockwell's Autonetics Division that year to develop the SHAPE (Scanning Hartman Aperture Plate Experiment) II scanning Hartmann wavefront sensor[23] for the Airborne Laser Laboratory (ALL) program. However, by the time I arrived in early 1982 that assignment had been filled by staff engineer Fred Tart. I was reassigned and put in charge of evaluating and qualifying a suite of four "laser diagnostic" instruments located at a "downrange" site blockhouse used to help characterize the power, irradiance and pointing performance of low power samples of the High Energy Laser (HEL) 10.6 micron wavelength beam output of the ALL GDL laser system. This testing venue building had openings to receive various orders of diffracted beams from a grating on the ALL aircraft for diagnostic sampling purposes.

This period followed the earlier unsatisfying attempted "shoot-down" demonstration of a missile in June of 1981. As a result of that experience, numerous subsystems and capabilities were being reviewed, upgraded and prepared prior to future planned testing. I was fortunate to arrive to be part of that troubleshooting and improvement effort and contribute to that next subsequent shoot-down demonstration[24]. Following the successful performance of the ALL in shooting down missiles with a HEL beam in the spring of 1983, I received a new subtask technical lead assignment to create laboratory diagnostics including a wavefront measurement system for the Air Force LOCS (Local Optical Correction System) program.[25] Also added were technical support assignments on the PHASAR subtask (including performing initial manual optical phasing and contributing to its diagnostics), and scatter measurement capability upgrades to the Grating Efficiency and Measurement Apparatus (GEMA) including helping to rename as GEMASIS[30] (Grating Efficiency Measurement Apparatus & Scatter Inspection System). Thus the OSC education helped make my 30-months experience at the AFWL (1982-1984) a career highlight.

Experience with shear plate pairs and PDIs as laboratory diagnostic wavefront sensors led me to search in the 1980's for a simple, universal, compact, phase-shifting-capable wavefront sensor for use on laboratory test tasks at Rocketdyne, California, where I transferred to in 1984. I learned in probably about 1986 or 1987 about a self-referencing Mach-Zehnder pinhole interferometer, which I shall refer to as MZPI, or alternatively MZIP (Mach-Zehnder internal pinhole) wavefront sensor, depending upon the application. I did not know about the internal MZPI design (see Figure 7) of WYKO's Ladite[26] product at this time but it appears to be one of the earliest references. This concept seemed like a good candidate for my objectives so I secured "overhead" budget funding and assembled a small brainstorming group to deliberate on candidate interferometers and associated equipment upgradable to a phase-shifting measurement system. After the second meeting we all became too busy with other assignments to continue that project. That was unfortunate, as we might have contracted WYKO to do some development because Larry Rubin (an OSC graduate) had already identified WYKO as a vendor of interest. But my hunch that the MZIP approach was superior was not invalidated.

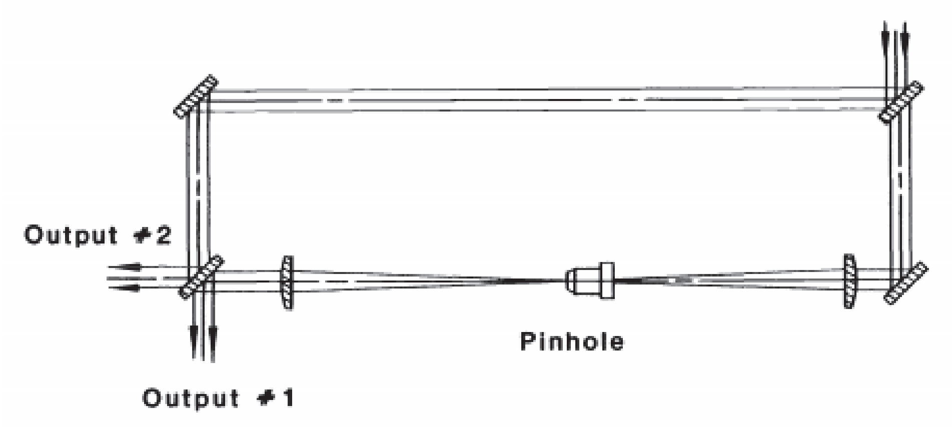

Figure 7. MZPI schematic for WYKO Ladite product[26]

In 1988 I built a (non-phase shifting) MZPI very different from the Ladite configuration or any other to my knowledge: a 4"x6" prototype referred to simply as the SRI (self-referencing interferometer). I once used it on a laser test where I bore sighted the pinhole to the position sensor of a mirror stabilization system and the results were very successful. It later evolved to a more miniaturized version ("mini-SRI"). In 1995 I was going to patent a "micro" version, but in the prior-art research process I discovered the Wilcken interferometer[27] had just been patented. That discovery, coupled with elapsed time and other factors persuaded me to not pursue it. But it eventually led to the author's MEMS patent (described in Section 6). The success of my SRIs was very helpful in my career for many years, and contributed to my becoming a Boeing Associate Technical Fellow. Thus, James Wyant also may have influenced that with Ladite.

One interesting aspect of the MZPI is its origins. James Wyant remembers[28] thinking of it independently for Ladite, but doesn't know if someone else may have also thought of it. I have not yet found a reference of anyone claiming to have invented the MZPI concept. In addition to the Wilcken interferometer mentioned above, of interest is a different MZIP wavefront sensor configuration that was conceived and proposed by Angel[29] for an adaptive optics application in a 1994 publication. From this author's research over the years, James Wyant appears the most likely inventor of the MZPI.

The ALL experience and related work at Rocketdyne led almost two decades later to work on the 1.3-micron wavelength HEL successor to the KC-135 aircraft ALL: the 747 aircraft Airborne Laser (ABL). In that subsequent program I helped successfully develop with Boeing subcontractor Lockheed-Martin a flight-worthy multi-wavelength BTA (beam transfer assembly) diagnostic bench suite to provide information on the laser beams of that system. Thus, ironically, 20 years after the missed ALL wavefront sensor opportunity, I incorporated a different type Hartmann sensor on a different aircraft type! As part of that work I was recognized in 2003 "For outstanding contributions to the development, integration and test of the Airborne Laser's diagnostic assemblies."

After completing the BTA bench, but prior to its flight testing, I retired from Boeing and began work at Northrop Grumman in Florida, where I had additional opportunities to work test engineering and integration functions with beam diagnostic test equipment for their multi-function rangefinder products. But the course content and the quality of the educational instruction at the OSC and especially in the first 1975 Wyant optical testing class had led directly to the succession of the interesting assignments described above (and others subsequently described in Section 5) in the area of optical testing and beam diagnostics, often referred to as simply "diagnostics." In this field I had the great fortune for decades to work intimately with the characteristics of the phenomena of electromagnetic radiation that Einstein referred to in Section 2, spectrally from the ultraviolet to the infrared, measuring not just wavefront phase, but also power, irradiance, wavelength, frequency lineshape, coherence, pointing, and various industry definitions of "beam quality."

Finally, Professor Wyant was also an educator to the wider optical and related community beyond the University of Arizona. This has been not only via just professional journal articles (where he has been prolific with "JOSA," "Applied Optics," "Optical Letters," "Optical Engineering," and others) but also with trade magazine examples such as Laser Focus[1,31], Laser Focus World[32], SPIE OEmagazine[33], and others. With printed and spoken words he kept the photonics industry up to date on the evolution of the phase-shifting analysis revolution while delivering optical metrology hardware over the decades. Founders Oersted and Faraday did something similar, with their popular science lectures to the public.

5. OPTICAL PHYSICIAN

5.1 A model borrowed from medicine

In the field of medicine physicians will often start with a troubleshooting consultation, move to a diagnosis, and then to a corrective action prescription (Rx). Some medical professionals are also researchers while others create products based on their experience, resulting in helpful instrumentation and methodologies for medical progress. These processes are applicable to the photonics craft for troubleshooting and test certifications as well as instrument development work.

The wide range of testing methods exposure, especially for wavefront error determination, led me naturally to a career path involving optical metrology, laser beam diagnostics, and troubleshooting. These were major constituents of system integration and test operations which led me into that type of work which provided job security (and sometimes deployment opportunities) in hardware-oriented companies. (It was embarrassing at one point when I and others with similar skills were in high demand and getting raises while several of our co-workers were being laid off.)

This metaphorical label of "Physician" is assigned to Dr. Wyant primarily due to his interest and success with research and development and marketing of wavefront diagnostic and other optical metrology instrumentation used to find truth: certify "health" of systems or surfaces, or identify a "malady" or defect requiring a corrective action "prescription" or rejection. But one would expect it to also be a feature of his professional industry consulting as well.

Consistent with this "medicinal" aspect model of Wyantism culture, those of us in photonics program test and integration (T & I) hardware work were also always diagnosing issues, while sometimes also developing new tools to do the work better or other times procuring from vendors. This was true also with the author when employed at Northrop Grumman in Florida developing diagnostics for low power systems such as multifunction rangefinders. OSC courses like Optical Testing, prepared students for this type of work just as for traditional optical engineering design. I considered T&I the "end of the food chain" of program hardware development (especially on large programs), where all hidden problems finally are exposed, often with little program schedule time left. It's likely that Dr. Wyant also even had to self-diagnose his own diagnostic instrumentation during development.

5.2 1974-Wyant interview and a memorable diagnosis example

Soon after I began my graduate work at the Optical Sciences Center in the fall of 1973, I became a Research Assistant on a Robert Shannon project entitled "Large Diameter Active Mirror with Holographic Figure Sensing" for the Space and Missile Systems Organization of the AF Systems command[34]. My assignment was to investigate the feasibility of etching an off-axis diffraction grating onto the surface of a mirror. This grating would diffract and focus light into a figure monitor for closed loop control of the surface figure. Part of my research involved creating off-axis zone plates with a holographic recording configuration.

In April of 1974 I assisted with the set up and operation of a holographic interferometry[35] bench configuration to test results from commanded surface deformations of a deformable mirror plate. In this process one first records a hologram of the wavefront reflected from the optical surface. Then, when the processed hologram is replaced in position and the system is re-illuminated, the resulting interference between the initial recorded surface wavefront and the new "live" surface wavefront reveals fringe contour distortions to be analyzed and compared with computer predictions.

Initial measurements had been disappointing because fringes were hard to discern because of irradiance nonuniformity resulting from self-interference from the non-imaged surface distortions, (as shown to a slight degree, probably from imperfect imaging, in the upper left interferogram in Figure 8). By coincidence, about this time James Wyant happened to be visiting the OSC (associated with his interview trip), and he visited our lab. He proposed adding a field lens to image the surface[36] of the mirror onto the observation plane. One was added, and this provided the clear interferograms shown in figure 6. When processed, these interferograms were found to agree well with computer predictions.

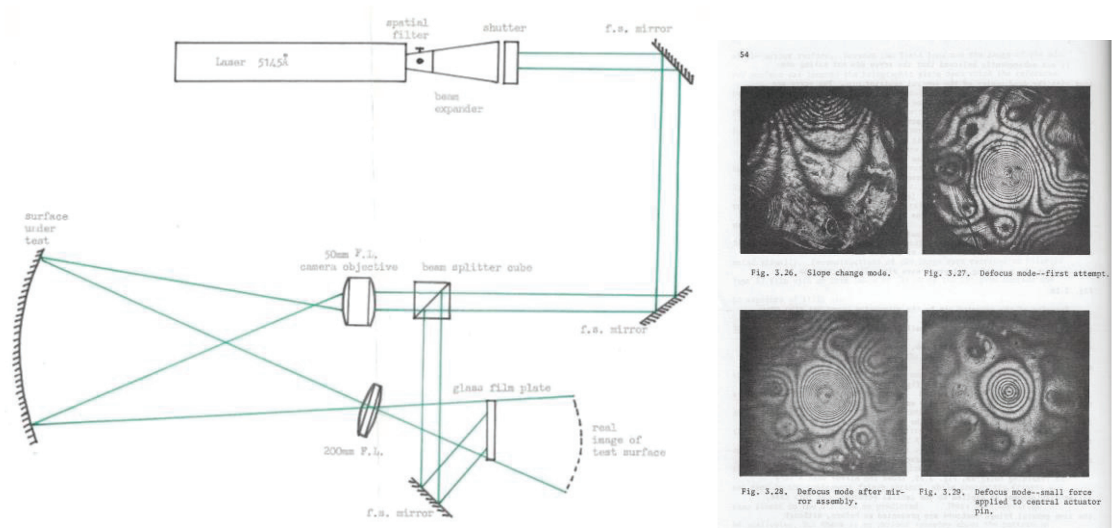

Figure 8. Optical Layout 6 April 1974 and resulting holographic differential interferograms[34]

Wyant also once cleverly solved a problem that he couldn't solve by himself – by buying the company that did solve it! (See Section 6.1 below).

Time and clearance issues obviate elaborating on many of the author's troubleshooting experiences. On ALL in 1982 I did troubleshoot and fix a repeatability problem with a low power integrating sphere test device which suffered from inadequate scatter (as well as perceived detector ringing that was really Fresnel diffraction effects). Although I am also not permitted to describe the details of another experience in 1991, I was recognized for my efforts performing optical troubleshooting work on a different project: "Mr. Larry Brooks . . . drew a number of problems that had other individuals baffled. Through systematic, professional, application of troubleshooting techniques he was able to engineer solutions to several critical measurement problems. His resolution to these problems modified our view of the system hardware. His dedication, professionalism, and contribution . . . should be recognized." These examples are shared to illustrate the effects of the education that was provided by Dr. Wyant and the Staff of OSC that many never see or hear about because they are typically not published, but they are critical issues in programs in integration and test.

But I experienced both successes and failures in my role as "physician" troubleshooter. I made mistakes sometimes but I learned some lessons as well in this function. James Wyant is quoted in the next Section as saying that you are not trying if you are not making mistakes, although some of mistakes were avoidable. Here are some observations:

1. Follow Professor Wolfe's phrase: "Think of everything." Stare at the system for as long as you can while pondering.

2. Invest time immersing yourself into learning completely the system you are troubleshooting; then you become part of it and can "look" around from the inside and "see" potential issues. (Once I solved a problem by discovering a beam splitter was behaving like a shear plate, but only after staring at dozens of repeated reruns of a short camera recording)

3. Don't be afraid to consult and deliberate with others; make sure you understand completely what they are saying.

4. Don't be intimidated by a hostile "owner" of a system under audit. Establish a friendly relationship but if that fails don't be afraid the to invoke management assistance. [(While tracking down a lost shipment of beamsplitters I was excluded from looking inside our receiving warehouse and searching myself. I resolved by filing a theft report with Security about the department. This gained me instant access and a discovery of the missing critical parts.)

5. Look for loose or broken parts. (advice from general US NAVY electronics training.)

6. Learn all you can of the history and personnel involved.

7. Most of the problems I solved were caused by either coatings, scatter, software or connectors.

8. Prove the problem diagnosis more than just one way if possible (ex: theory & experiment).

9. Most failures to correctly troubleshoot were due to not studying the system sufficiently

6. OPTICAL PRODUCER

6.1 A relevant producer model

The final person characteristic to be considered with "Wyantism" is that of "Producer," which implicitly includes leadership, competence and vision. From the Faculty Directory Resume[37] of Jim Wyant:

"Research Summary: My major research and development interests involve using interferometric techniques combined with computers and modern electronics to ***produce*** "state of the art" solutions for a variety of metrology problems." (underlined italics added).

Jim Wyant has reported[15,51] that when young he wanted to be a professor, an inventor, and to start and run a company. All three of those dreams were realized as seen by the "products" he has produced. Categories include not only graduated students, patents, and instrumentation, but also wealth, "investment" philanthropy and visionary roadmaps.

A review of the Wyant WYKO webpage[38] will reveal twenty WYKO hardware products produced over decades that testify to his success in starting and running companies. He co-started a company in 1982 (WYKO) that he eventually took over and later sold. Subsequently he purchased an Irvine, California, company (4D Vision Technology, Inc.) because of their ingenuity in overcoming the PSI vibration problem and using it co-founded another (4D Technology Corporation). In the 2007 Spring/Summer issue article[39] "20/20 vision" by Dana Wier of the University of Arizona Foundation magazine "Advancing Arizona," he was reported as saying the following: "I always liked to make money. When I was young, I started out with two little businesses." His innate tendency towards financial success through hard work and apparently good business sense has allowed him to express immense philanthropy for not only both the growth of the Optical Science Center and assistance for students, but for the University of Arizona and our industry as well.

He has been a successful professor, earning progressively titles of associate professor, assistant professor, professor, and now professor emeritus. He has not only taught courses, he has produced 25 Master of Science graduates[40] (including this author, his second one, in 1976) and 34 PhD graduates[41]! And those student "products" have also become producers, some in business like their advisor.

He has also achieved becoming a successful inventor with 10 patents[42]. More have undoubtedly been created by students and other professionals he has inspired.

And mostly related to these three areas is a list[43] of 19 awards and honors, including the invention, business or hardware related awards like the following: 1992 Joseph Fraunhofer Award; 1993 Arizona Inventor of the Year Award; Phonics Circle of Excellence Awards (1990, 1992, 1993, 1998, 2004); SPIE 2010 Chandra S. Vikram Award in Optical Metrology; SPIE 1998 Technology Achievement Award; 2005 Tom Brown Excellence in Entrepreneurship Award; 2005 U of A Technology Innovation Award1989 U of A College of Business and Public Administration Entrepreneurial Fellow; 1994 Univ of Rochester College of Engineering Distinguished Alumnus Award; and the 2003 SPIE Gold Medal - the highest honor the Society bestows ("Since 1977, it has been awarded in recognition of outstanding engineering or scientific accomplishments in optics, photonics, electro-optics, or imaging technologies or applications.")

The saying goes, "If you fail to plan, you plan to fail." But James Wyant had a plan early in his life. He once briefly mentioned it to this author, and I recall some parts. He was going into the optical field; would work in industry for a while; then take a position in academia; then have a business; then return to academia. This planned cycling could be construed to be strategic part of Wyantism. It would seem apparent that this plan would require preparation with correct principles: learning optical sciences and business as well as having an action plan. But regarding failing, Producer Jim is in the Wier article[39] reference above as quoted as saying, "You have to take risks and not be afraid to fail. If you don't fail occasionally, you're not trying enough new things."

6.2 Personal application examples: planning and inventions

Wyant's example of having a goal plan coupled with my introduction to patents because of him (described in Section 4.2) may have inspired my actions in 1989 to try an experiment. I decided to file patents on four ideas to see what would happen. That resulted in two "product" patents: one (technically a "Statutory Invention Registration") in 1990[44] for which I also received a Rockwell International Meritorious Disclosure Award from the company Patent Department, and another in 1991[45]. However, neither to my knowledge were ever developed into products or even prototypes.

In the late 1990's my company had an initiative to "help you improve your performance through development of your skills and abilities." While some associates seemed annoyed at this as a bureaucratic nuisance, I think exposure decades earlier to James Wyant's concept of planning helped me to take a different view. I saw opportunity to encourage the system to schedule and budget training in areas of relevant personal interest, like MEMS (micro-electrical mechanical systems). As a result, in 1999 I attended a course titled, "Microphotonics: Integration of Optical Systems Based on MEMS Technology" through University Extension at the University of California in Berkeley. This eventually led to a MZPI "product": a MEMS optical patent awarded in 2008 [US7,379,191] of a micro miniature "combination-interferometer" diagnostic[46]: "Optical MEMS Diagnostic Transceivers and Receiver". It was also never developed to my knowledge.

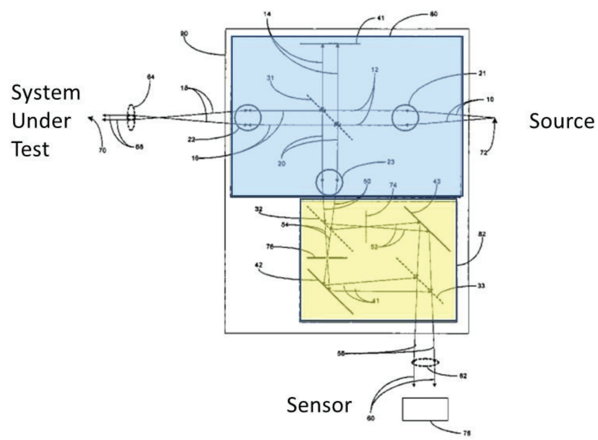

Figure 9. Optical diagram from Patent 7,379,191, "Optical MEMS Diagnostic Transceivers and Receiver"[46]
(Blue top stage: Twyman-Green, yellow bottom stage, MZPI)

An effective producer will create value for others. Thanks to his business skills James Wyant is also well-known for his generous philanthropy to his craft. The following are just some examples from references [39,47,48,49,50,51,52]. Most remarkable is a $20M endowment to the College of Optical Sciences on 30 November 2018 for endowed chairs; this was reportedly the largest of its kind in the history of the University of Arizona. The University of Arizona President said that the resources would help the university "achieve the goal of being a leader in the 'Fourth Industrial Revolution'." Previously "In 2013, James Wyant made a historic $10 million gift to the college for graduate student scholarships in a campaign called FoTO, an acronym for Friends of Tucson Optics. As a result of his initial gift, more than 250 additional donors contributed and 30 first-year graduate student scholarship endowments were established, each bearing the name of a donor." About the philanthropy Wyant said, "I am especially grateful to the university for its incredible flexibility when I was partway through my teaching career and wanted to start a company (WYKO). The financial success of that business has made these gifts possible." The leading reason for his gifts, he said, is to "ensure a pathway for the College of Optical Sciences to achieve even greater prominence and success in its education and research mission." He also has remembered his undergraduate college, now called Case Western Reserve University, making millions in donations to the Wyant Athletic and Wellness Center and to the Case School of Engineering's innovation hub. Time prevents further research and reporting of this admirable feature of James Wyant.

Through his WYCO and 4D Technology Corporations, his entrepreneurship and academia relationships, James Wyant led the development of numerous optical testing instruments during a revolutionary period in electro optics. One might say that he waded in and masterfully surfed that wave of phase shifting interferometry (also known as phase-measurement interferometry[53]) that was sweeping our optical metrology discipline in the photonics craft. But his business sense and associated personal goal models leave a continuing legacy of success and products, along with a recipe to be not just admired but analytically studied.

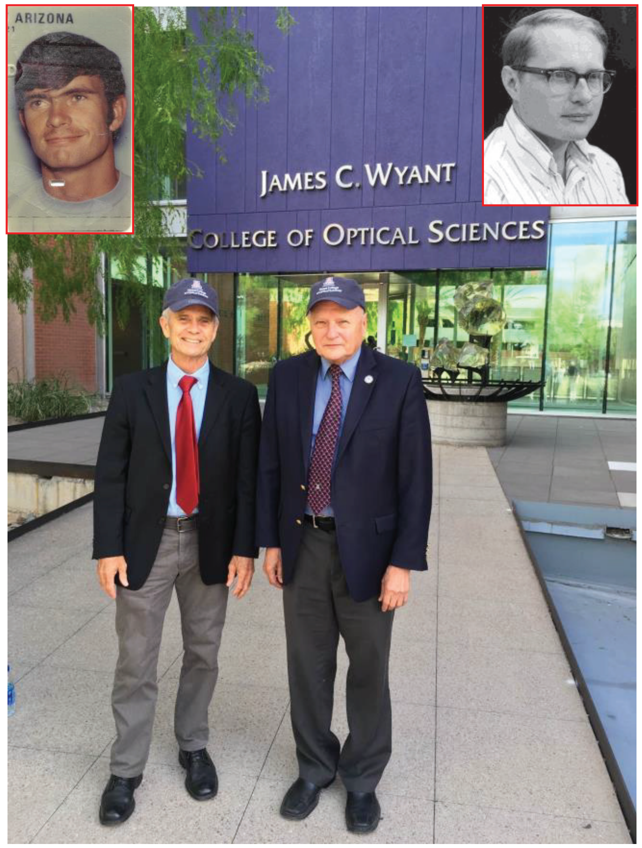

Figure 10. Now and then: The author (L) and James C. Wyant (R)
BOTTOM: At the 27 April 2019 dedication of the James C. Wyant College of Optical Sciences (© Lawrence Brooks 2019)
TOP: Inserts with author's U of A 1973 student picture ID (L) and Wyant[54] from 1976 (R)

7. SUMMARY

This document has attempted to honor Dr. James C. Wyant not only by the way he has directly affected the author's career, but also by his impact on our craft and the people that work it. It has also attempted to describe some of the features of Dr. Wyant through numerous ways that are representative of his interaction with others. Some of these include apostle, educator, physician and producer; his accomplished early personal goals as inventor, professor, and successful business owner; and in his philanthropy style. It was meant to be a representative sampling of the work and actions of Dr. Wyant based on the author's personal knowledge over the years, mingled with some hasty research. The term "Wyantism" was introduced to assign a label meant to capture the uniqueness of his approaches and consequential successes in optical metrology, optics education, business, philanthropy as well as vision. Homage was also paid to some of the early pioneer Founders of our craft who contributed by trailblazing through the unveiling, for our later utilization, of the phenomena of electromagnetic radiation. The short synopsis does not do justice to the amazing story of how they accomplished what they did, so it is hoped that section will stimulate interest and further reading.[8,11,12,13,55]

8. CONCLUSIONS

James Wyant has earned the label as giant not only because one could consider his particular accomplishments with phase shifting technology a productive movement heavily associated with "Wyantism." But it is through the combination of the four representative areas (apostle, educator, physician, producer; admittedly not a complete or unique set), coupled with his innate intelligence and upbringing, that one recognizes expressions of the person and his accomplishments, achieved in part through synergy between these elements. We are all fortunate to have survived a world pandemic to personally share in this SPIE honor to him.

In the course of the preparation of this manuscript there was some discovery. Not only was Oersted's discovery commonly thought to be accidental, but a reference[56] suggested Hertz's discovery of a needed detector might also have been part by chance. "Hertz was surprised to see sparks also coming from a stray wire . . . [and] found something Lodge had missed . . . something to 'feel' the waves with." And based on scattered research on patents and technical papers over many years, from the Ladite product in the 1980's, and recent communications with James Wyant, it appears that he may at least be a co-inventor of the Mach Zehnder Pinhole Interferometer. This author believes he may have been the first to envision it, and a more thorough research is justified. Subsequent version types played an important role in the author's career.

A book should be written about how Dr. James C. Wyant has been so successful so others might consider that recipe and continue his legacy. This SPIE tribute conference should go a long way to defining a true phenomenon which we know as "Jim." Reference 51 had a nice overview synopsis of key elements in James Wyant's life. That writer (Orr) or the authors of reference 10 (Forbes and Mahon) are good candidates to write a book about James Wyant.

In some ways the production hardware developed through James Wyant has already contributed to the contemporary industrial revolution[57] within photonics and optical metrology. As an example of WYKO's impact, Jim was quoted[51] as saying, "Essentially, every manufacturer of hard-disk drives in the world was using WYKO's equipment for evaluating hard disks and recording heads." We all rejoice in James Wyant's successes which are inspirational to all familiar with his work. Emily Dickenson's poem, "We Never Know How High We Are," is a reminder that each has a story to live, and we are obligated to try to live it to the utmost.

We never know how high we are
Till we are called to rise;
And then, if we are true to plan,
Our statures touch the skies—

The Heroism we recite
Would be a daily thing,
Did not ourselves the Cubits warp
For fear to be a King—

9. PARTING REMARKS

My five years at the Optical Sciences Center were among the most stimulatingly enjoyable and formative of my life, and my personally rewarding career path benefited directly from the teaching of and association with James Wyant. I had gone to the University of Arizona in 1973 expecting to quickly finish with a Master's degree and return to California to obtain a job. Instead, I acquired a career and a PhD. In that sense I sustain the comments of financial award recipient Kaitlyn Williams in a circa 2013 "OSC Giving Back Annual Campaign," newsletter, where she said, "Thank you [OSC]. . . for making me feel that I'm a part of something bigger than I had ever imagined."

This author would be remiss without an expression of gratitude to my Master's Thesis advisor Jim Wyant and Dissertation advisor Bill Wolfe, other key professors and staff of the Optical Sciences Center, to pioneers in our scientific field, to fellow students and peers, and to numerous managers and co-workers that I interacted with often under stressful circumstances in far flung assignment areas for over 43 years in this optical science and engineering "craft." I would also like to acknowledge the laboratory-rich physics environment at my undergraduate school Cal-State Fullerton (now California State University at Fullerton) where I first attempted holography, as well as my high school physics instructor William B. Rowley. I will not attempt to list all names as it will inadvertently leave off important recognitions.

I attribute my successes in greatest part to the strength of the educational network system at the Optical Sciences Center and will be always grateful for my association and the receipt of so much useful knowledge from my advisors and so many staff professors and office staff of that organization. Any limitations or shortcomings expressed in my career were due to me and not the institution. I think our craft and photonics in general is in good hands with an exciting vector under the current leadership of the Wyatt College of Optical Sciences, and it will receive the support needed to ensure it thrives as the greatest photonics and optical metrology institution in the world.

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