Seeing fringes everywhere: impact of James C. Wyant's contributions to optical metrology

Katherine Creath[1,4*] Joanna Schmit[2*] and Goldie Goldstein[3*]
[1]Optineering, Tucson AZ USA 85719
[2]Onto Innovation, Inc, Tucson, AZ USA 85706
[3]Nikon Research Corp of America, Tucson, AZ USA 85755
[4]Wyant College of Optical Sciences, The University of Arizona, Tucson, AZ USA 85721

ABSTRACT

Few in history have had as great an impact on their field of study than James C. Wyant. This paper provides an historical overview of Wyant's contributions to the field of optical metrology and how they have impacted today's technology. Beyond his role as an innovator, inventor, leader, enterpreneur and philanthropist he will perhaps be best known for his teaching and the legacy of the multitudes of students he taught over his career.

Keywords: optical metrology, optical testing, interferometry, interferogram analysis, computer generated holography, phase measurement, two-wavelength interferometry, Optical Sciences Center, College of Optical Sciences

1. INTRODUCTION

When James C. Wyant was in the fall semester of his senior year at Case Institute of Technology back in the 1960's, he saw his first hologram and laser. By his recollection he "looked through a cloudy piece of glass and saw a stapler." He tried to reach for it, and "of course it wasn't there."[4, 5] Jim found this fascinating and had to learn more about it. This led him to learn about optics and holograms which took him to the University of Rochester as a graduate student at the Institute of Optics studying under M. Parker Givens. He ended up doing his dissertation on holograms, and then got hired at Itek Corporation when he graduated to work on computer generated holograms for testing of aspheric optical surfaces.

Fig. 1. James C. Wyant in 1974 and 2014. (Photos courtesy of Jim Wyant).

From there his career took off down a path that pulled him to a teaching position at The University of Arizona's young Optical Sciences Center. While a Professor at The University of Arizona, from 1974-2012, he supervised 34 PhD students, and 25 MS students. Of us 3 authors, Kathy was PhD student #15 and Goldie was PhD student #34. Joanna was a student of Kathy's and thus is a "grand-student" of Jim who worked for many years with him at Wyko and 4D Technology.

While he was a professor, he was spurred on by one of the companies funding his research to create a commercial instrument they could use. This ultimately grew into Wyko (which then was bought by Veeco). After 13 years spending most of his waking hours at Wyko, Jim went back to OSC full time teaching. Then another major enterpreneurial opportunity came along that became 4D Technology Corp (now Onto Innovation, Inc) where he served as Chairman of the Board. In the midst of this, Jim led the effort to convert the Optical Sciences Center into a full-fledged College of Optical Sciences and became its founding Dean.

* email: kcreath@ieee.org; joanna.schmit@ontoinnovation.com; ggoldstein@nikonrca.com

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After retiring as Dean in 2012, Jim began focusing on philanthropy. He endowed chairs at University of Rochester, Emmanuel College and Case Western Reserve University. Then he offered matching seed money for the FoTO (Friends of Tucson Optics) scholarships that fund first year graduate students at the College of Optical Sciences. Once that was in place, he offered more matching seed money for endowed faculty chairs for the College of Optical Sciences. In 2019, the college was renamed the "James C. Wyant College of Optical Sciences" in his honor. His gifts help ensure that the future of the College is financially secure.

When most of us think of Jim Wyant, we recall his enthusiastic teaching, and the large numbers of students he taught over the years. That is what he is most proud of as his greatest accomplishment in optics.[4, 5]

2. EARLY YEARS

Jim grew up on a farm in rural Ohio. He was an enterprepreneur from an early age earning money to support himself and his mother after his father died in a farming accident. He did his undergraduate work in Physics at Case Institute of Technology (now Case Western Reserve University) graduating in 1965. Then he went on to the University of Rochester's Institute of Optics where he was a student of Prof. M. Parker Givens. After graduating with his PhD in 1968, he was recruited by Itek Corporation in Massachusetts.

While at Itek, he contributed a number of seminal papers to the fledgling field of laser optical metrology in the areas of computer generated holograms (CGHs),[6-10] testing of aspheric optics,[2, 9, 10] two-wavelength holography,[2] shearing interferometry and grating interferometry.[1] His articles from this era were pioneering for each of these different aspects of optical metrology.

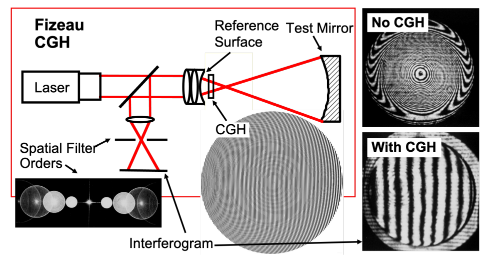

Fig. 2. Today we can make a CGH placed in front of a Fizeau interferometer to test an asphere. From [3]

In 1969, CGHs were in their infancy compared to now. You'd have to calculate and draw the hologram onto a large piece of paper, and then photograph it onto film at the correct size for where it needed to be placed in the interferometer.[3] Today you can send your optical design data to a company that will generate and send you a mounted CGH etched on a glass substrate that you pop into a fixture in front of your commercial interferometer (Fig. 2). Hopefully, in the not too distant future, we'll be able to program any wavefront into some sort of wavefront modulator that will create a null wavefront with megapixel resolution.

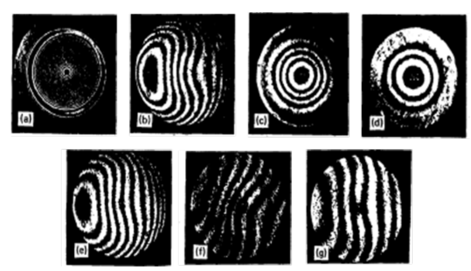

Fig. 3. Interferograms from two-wavelength holography obtained at different equivalent wavelengths. From [2].

Another innovation at Itek was two-wavelength holography. Jim had the idea that you could make a hologram of an optical surface at one wavelength and then change to a different wavelength to get a desensitized interferogram that you could measure at a synthetic wavelength by looking at the beat pattern as shown in Fig. 3. [2] Kathy later took that concept and applied it to phase shifting so that multiple wavelengths could be used to test an object and unwrap discontinuities created by having a large amount of interference fringes present.[11, 12]

Also while at Itek, Jim developed a crossed-grating two-frequency lateral shearing interferometer that allowed surface slope to be measured simultaneously in two dimensions. By shifting the gratings relative to one another (or by changing the frequency of one grating relative to the other), you could change the relative shear and thereby choose the test sensitivity.

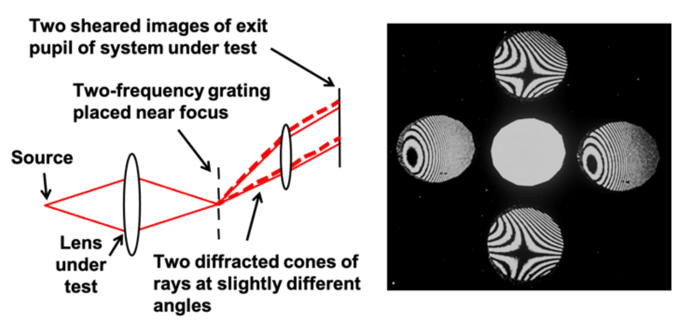

Fig. 4. Crossed grating two-frequency lateral shearing interferometry. From [1].

These sorts of ideas can be seen in commercial interferometers today as shown in Fig. 4. [1]

Back in those days the tests were still mostly qualitative compared to what we have today. You either took a photograph of the interference fringes or you had a few point detectors and you tried to infer the phase difference between them. You can see from these early results that data quality was not as nice as it is today. What really moved things forward were advances in computer technology and digital cameras.

3. INTERFEROMETRY AND PHASE MEASUREMENT (UARIZONA) – *K. CREATH*

While at Itek he worked with Prof. Bob Shannon and Bob Parks. This was a very fruitful time for him as he developed the basics of what would be his research program in fringe analysis, phase shifting interferometry and computer generated holography.[13] In 1974, Wyant was offered a position at the Optical Sciences Center of The University of Arizona.

Jim brought the concepts of phase-shifting interferometry to OSC from his days of working on classified projects at Itek. His lab produced a number of PhD's related to improving phase-shifting techniques and applying it to every kind of interferometer and fringes you can think of. Those of us who worked then in the lab were looking at ways to phase shift everything. Jim had a list on a piece of yellow lined paper that had more than 30 possible topics he wanted to work on as ideas for students.

One of the biggest issues in optical metrology was analyzing and quantifying the fringe patterns. Before phase shifting interferometry was practical, interference fringes on a photograph were scanned with a measuring microscope and the fringe centers entered into a computer program so that the inevitable tilt and defocus could be removed from the information about the mirror surface.

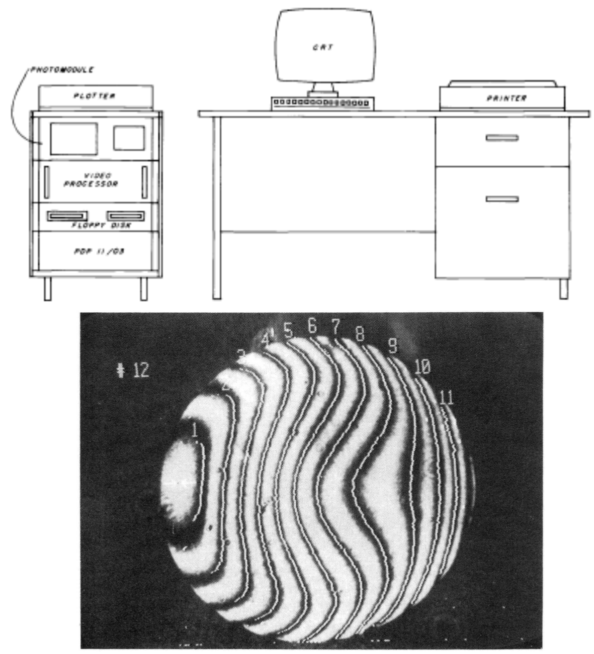

Fig. 5. Microprocessor-based instrument for analyzing video interferograms (top) and an interferogram with fringe centers and order automatically processed (bottom). [Ref. 21].

The first program for analyzing interferograms FRINGE was written by Jim Rancourt, PhD 1974,[14] but the only computer at the time capable of handling the data was the main frame at the Computer Center several blocks away. This meant carrying boxes of IBM punched cards across campus and hoping that every punch was exactly where it should be, or it was another overnight computer run. Of course these test data runs competed with those wanting to run optical design programs for computer time. It wasn't until 1979 that results from the video scanning system were reported by Ken Womack, PhD 1982, and members of Jim Wyant's lab (see Fig. 5).[15] Later, John Loomis, PhD 1980, wrote a FRINGE MANUAL, and updated the program to output the 37 "FRINGE" Zernike polynomials,[16] and with it, the confusion about whose numbering of the polynomials one might be using.

In the early 1980's, Jim wrote a commercial fringe analysis package which he called WISP (Wyant Interferometer Software Package) in Pascal. It allowed the user to input data points along fringe centers using a digital tablet. He initally marketed this through Zygo for use with their Mark II interferometer, and later it became a WYKO product.

Many of these contributors are shown in Fig. 7. Rich Shagam (PhD 1980) developed the mathematics and algorithms for heterodyne and moiré analysis of interference fringes providing the basis for many other student's work.[17] Chris Koliopoulos (PhD 1982) implemented phase shifting on many systems including a phase-shifting interference microscope.[18] Besides building many interferometers, John Hayes' (PhD 1984) dissertation focused on developing feedback from interferometric measurement for computer-controlled polishing.[19] Yeou-Yen Chen (PhD 1985) worked on two-wavelength phase measurements (see Fig. 6).[20] Kathy Creath (PhD 1985) developed

Fig. 7. Wyant students who contributed to early days of phase-shifting interferometry. From left: Rich Shagam, Chris Koliopoulos, John Hayes, Yeou-Yen Chen, Kathy Creath and Chiayu Ai.

techniques for digital speckle pattern interferometry (now known as digital holography) for measurement of deformation, vibration and shape (see Fig. 8).[21] Chiayu Ai (PhD 1987) worked on the precision and accuracy of phase measurement techniques, and absolute testing and calibration.[22]

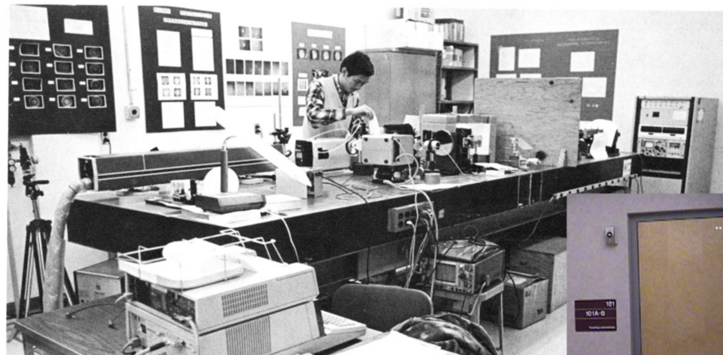

Fig. 6. Wyant interferometry and optical testing lab in OSC 101 ca. 1985 with Yeou-Yen Chen. (Photos courtesy of Jim Wyant).

Jim's lab in OSC 101 (see Fig. 6) was many stories underground with no windows. We often worked in the dark because someone wanted the lights off for their experiment. (This is how KC learned to type.) The OSC 1st-floor basement was designed and built with environmental precautions to get good interferometric data. However, the motion of the elevator, as well as trucks driving along University Blvd., could be measured in our data by our very sensitive experiments. Thus, we were known to come in at 2 am to take good data when the elevator wasn't running.

Fig. 8. Kathy Creath at 1985 OSA Meeting in San Diego with demonstration poster for DSPI - digital speckle pattern interferometry (now known as digital holography). (Photo courtesy of K. Creath).

These new techniques revolutionized phase-measuring interferometry and made it something that every lab and shop could own. They have been very influential in the field of optics. Six of the top 50 papers cited in the first 50 years of Applied Optics are on phase-measuring interferometry.[23]

Having on-site, easy-to-use metrology tools was a huge boon to the optical fabrication industry. There have been a number of spin-off companies from OSC that sell instruments based on the technology developed at OSC. They include Wyko Corp (later bought by Veeco Instruments and now Bruker Nano), Phase Shift Technologies (later ADE Phase Shift, and then bought by KLA-Tencor), Zemetrics (bought by Zygo), ESDI (Engineering Synthesis Design, Inc bought by Mahr), and 4D Technology Corp (bought by Nanometrics and now Onto Innovation). Along with Zygo Corp (now owned by Ametek), these companies have helped shape and lead the optical metrology industry over the last 30 years. A review of the work done in the Wyant lab on the development of phase shifting interferometry techniques was published in Progress in Optics in 1988. This made

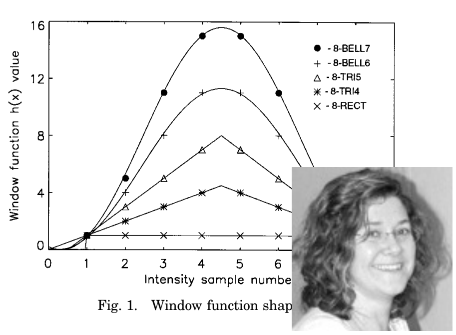

Fig. 9. Joanna Schmit and algorithm design. [Ref. 57].

the work accessible to researchers around the world.[24] This monograph has been cited more than 2000 times, and phase measuring has become part of mainstream optical testing.[25]

During my (Creath) first stint teaching at OSC from 1991-1995, my research followed a trajectory similar to that of Wyant's in optical metrology. Research from my lab included a liquid-crystal polarization PDI (point diffraction interferometer) by Carolyn Mercer, PhD 1995, (NASA Glenn Research Center) for optical metrology of wavefronts in wind tunnels,[26] and phase-measurement interferometry algorithm development and error analysis by Joanna Schmit, PhD 1996.[27, 28] The Schmit-Creath algorithm is still cited in many papers, and was one of the editor's picks for the top 20 optical testing papers in the first 50 years of Applied Optics (see Fig. 9).[27]

4. INTERFEROMETERS GALORE (WYKO) – *J. SCHMIT*

Jim Wyant strongly believed in the power of computers, fringes and graduate students; in the early 1980s he used all three to bring his automated phase shifting interferometry (PSI) for surface characterization into reality. Although the power of computers, solid state detectors and electronics was nowhere close to where they are currently, his strong conviction and perseverance led the team of a few intrepid graduate students and their plucky professor to develop an interference microscope with automated fringe analysis and found WYKO, his company to market this instrument, all while still teaching at OSC. He was WYKO's president and board chairman from 1984 to 1997.

Jim was a professor at the Optical Sciences Center at the University of Arizona where he first researched fringe tracking in interferometry and later phase shifting interferometry. He saw promise in PSI as computer processing power quickly improved. Soon, IBM became interested in his work on surface measurement, and this encouraged Jim to start a company with IBM's down payment for the first TOPO 3D optical profilometer series. This down payment gave WYKO a solid start, and over a period of 15-20 years, IBM would order over 100 WYKO systems. It was a good return on investment for both companies.

Fig. 10. (top) Early Wyko product line based upon HP Workstations: Topo, Sirus, and Ladite. (bottom) Wyko products from 1990's using PCs: 6000, RST, and NT2000. (Photos courtesy of Jim Wyant).

Creating a company takes a special person with both an eye for emerging technology and a steady hand for management and sales. Jim has both. He has a gift for motivating people to work hard and still be open to creative solutions. Jim's success is built on his own tireless work ethic and his dedication to an idea. In addition, he also believes in other's ideas and is committed to their success. Many variations on interferometers were built at WYKO (Fig. 10): interference microscopes initially used mainly in surface metrology, portable interferometers if a sample could not be brought to the system like print roller, large aperture interferometers, interferometers to measure the inside walls of a car engine, multiple fiber optics ends measurement, transparent film thickness measurement, double-sided disk surface measurement and even the first fringe projection for foot shape measurement, which did not become a product for a long time.

Jim was determined and sometimes single minded. He could be hard to convince. It was this way when white light interferometry was just beginning to be developed. His beloved PSI method had its limitations and he was trying to expand the range of its applications by working on systems of longer wavelength, two wavelength systems or a fringe projection system. After working on fitting the envelope to a few points of a white light interferogram with Paul Caber,[29] the potential of WLI caught Jim's attention (see Fig. 11).

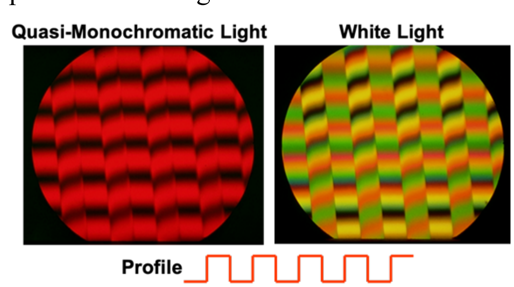

Fig. 11. Interference fringes for a diffraction grating.

Then, his students and employees came up and patented a method using centroid calculation for determining envelope position.[30]

It was during the times when computers were still a bottle neck for fringe pattern analysis that algorithm simplicity was a virtue. When I was developing some PSI algorithms (I was then Kathy Creath's student, and by Jim's definition his "grand" student), we thought that my 5-9 and up frame algorithms looked promising, but no one would use more than the 6 frame algorithm because of the limited computing power of computers.

Currently, many very sophisticated algorithms exist, but Jim in general likes simplicity and elegance of the solutions. The interference microscope systems with WLI option allowed for all sorts of surface finish measurement and heights over a few millimeter range and became by far the most sold system called an optical profiler. Optical profilers were no longer systems mainly for the data storage industry but also for semiconductor, material science, paper, printing, automotive, ophthalmic and many many other fields and industries as can been seen in Fig. 12.

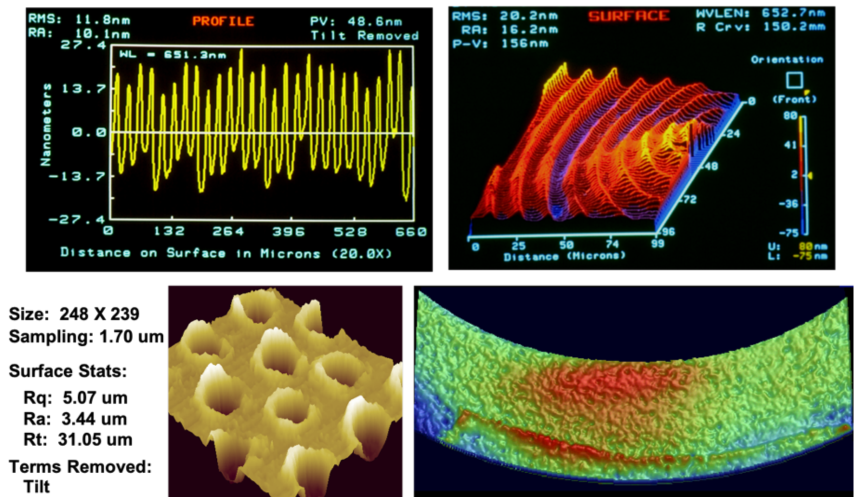

Fig. 12. (clockwise from top left) Diamond turned surface: Topo 2D and Topo 3D measurements. Stitched subregion of a fuel cap. Tiny pits in metal surface. (Photos courtesy of Kathy Creath and Jim Wyant).

In the early years of WYKO, Jim realized the need for intellectual property protection and forged a relationship with a local attorney who had engineering background. He quickly grasped the optical principles behind interferometer systems and collaborated with Jim's companies for many years. Now that the initial patents for optical profilers have expired, multiple new companies have arisen adopting these technologies, once again proving how important optical profilometry is within the field of optical metrology. Having created multiple well-used products and a large intellectual property portfolio, Jim decided that it was time to go back to full time teaching at the university instead of retiring after selling his beloved WYKO company to Veeco Inc in 1997.

Jim always wanted his students, workers and company to be a part of a broader optics community and in particular SPIE. Every SPIE conference in San Diego, people can participate in his shortcoarse on his beloved topic of Optical Testing. He himself was SPIE president in 1986 and a recipient of multiple SPIE awards; SPIE Technology Achievment Award 1986 (with WYKO), SPIE Gold Medal in 2003, SPIE Chandra Vikram Award in 2010, and recently SPIE Visionary award. Jim's vast contributions to the field of interferometry were recognized by his interferometry colleagues in the informal Holo-knight society. In 2013 Jim was "holo-knighted" by Lady Cristina Trillo Yanez from Vigo at the Castle of Ludwigsburg (Germany). Fig. 13 shows Jim


Fig. 13 Jim Wyant (with sword) after his holo-knighting ceremony. (Photo courtesy of Wolfgang Osten)

(sword in hand) with optics holo-knight colleagues from around the world after his holo-knighting ceremony

Kathy, Goldie and I, along with other optics people were part of Jim's journey, as we were first his students and then employees in his multiple companies, as well as active members of SPIE. We feel very proud to be part of his successes and we appreciate his technical, and financial support of optical sciences.

5. VIBRATION INSENSITIVE INTERFEROMETRY (4D TECHNOLOGY) – *G. GOLDSTEIN*

There was always a recurring theme amongst the many innovators who worked alongside and studied under Jim: Got fringes? What can we do with them? This was reflected in so many of the dissertations and published work of his graduate students as well as the countless products developed by his related companies and teams of engineers.

In the years that followed Wyko, Jim returned much of his attention back to his students at the Optical Sciences Center. During this time, his student Mark Neal, developed a polarization phase-shifting point-diffraction interferometer [31]. Then came Michael North Morris, currently Director of Product Engineering at 4D Technology, who developed a phase-shifting birefringent scatterplate interferometer [32].

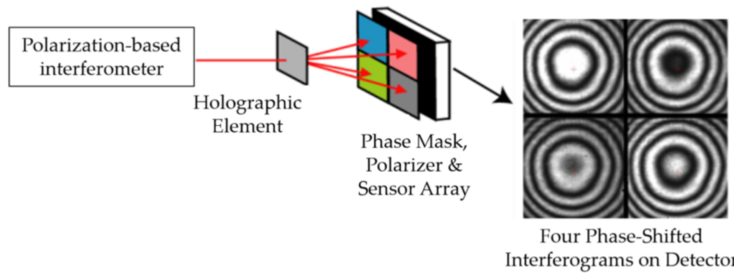

Fig. 14. Dynamic interferometry using a holographic approach. Adapted from Ref. [3].

Also during this time, a major shift in interferometry was starting to take shape. Just like the arrival of the laser altered the history of metrology, so did the concept of simultaneous phase-shifting to interferometry. James Millerd and Neal Brock had a startup called 4D Vision that was commercializing a holographic-based approach to simultaneous phase-shifting interferometry as shown in Fig. 14. A polarization-based interferometer was used to create 4 phase-shifted images of a test part falling on a detector simultaneously.[33, 34]

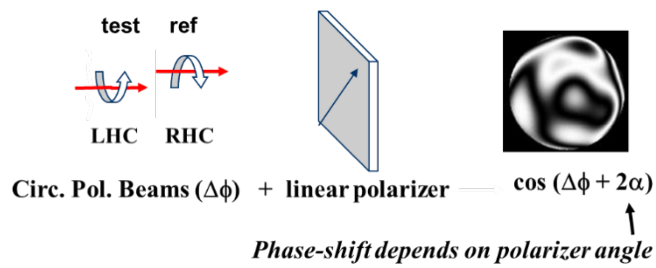

Fig. 15. Orthogonal circular polarization incident on a linear polarizer results in a variable phase shift between the two beams related to the angle of the linear polarizer. From [35].

Jim and John Hayes went to visit 4D Vision, and there they saw, what was and still very much is, one of the best interferometry demos (in my opinion): an interferometer on one table and a test part on a separate table. In Jim's own words, "I had to have it" [35]. 4D Technology became established soon thereafter.

The holographic phase-shifting technique had some limitations such as dispersion and chromatic distortion that limited its application. As the story goes, Jim was teaching an Optical Testing class in the old Meinel building. He was teaching the concept in Fig. 15, discussing how orthogonally circularly polarized beams would not interfere unless they were sent through a linear polarizer, and furthermore, you can change the phase by rotating the polarizer. It dawned on him that this was the technique they

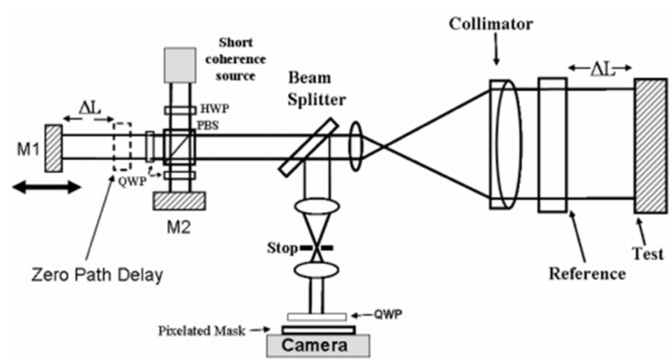

Fig. 16. On-axis dynamic Fizeau configuration where short coherence is used for surface isolation by adjusting mirror M1 [11].

should use for making measurements in the presence of vibration. He had trouble teaching the rest of the class because he was so excited about the idea.[5]

What came out of this lightbulb moment, together with the work of James, Neal and John (and the other early 4D employees) was the development of the pixelated phase-mask interferometer. One early interferometer type adapted for simultaneous phase-shifting was a Twyman-Green as shown in Fig. 16.[36] By utilizing a polarization-based interferometer in combination with a pixelated polarization phase mask aligned to a detector array, four phase-shifted interferograms were acquired simultaneously. This method was advantageous to its prior hologram implementation because it was achromatic, without distortion and compact. [37]

Now instead of having the vibration or air turbulence be the limiting factor in a measurement, it could also be the measurement target. Phase movies could be acquired, capturing the effects of hot air meeting cold air as a coffee cup was placed in the path of an interferometer, or cold water dispersing in warm water in a transmissive measurement as shown in Fig. 17. These novelty images and movies were just a simple way of showing the utility of simultaneous phase-shifting technology.

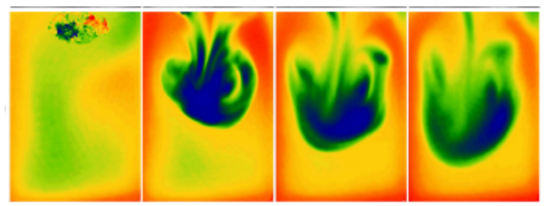

Fig. 17. Phase images of a time series of cold water dropped into cuvette of warm water [9].

Jim served as the board chairman of 4D Technology from 2002-2018. The interferometers and advancements in testing during this time period are numerous. Just like in the Wyko-era, the quest was on to find out how to apply simultaneous phase-shifting to as many applications as possible.

Learning how to fully understand the properties of the pixelated phase-shift technique and how to overcome errors to improve performance became important areas of research for Jim's students and 4D Technology's engineers under Jim's guidance.

Examples include Matt Novak's dissertation, PhD 2005, on utilizing a micropolarizer phase-shifting array that encodes phase shifts on a pixel by pixel basis [38] as well as Brad Kimbrough's dissertation, PhD 2006, developing a path-matched vibration-insensitive Fizeau interferometer as shown in Fig. 18.[39]

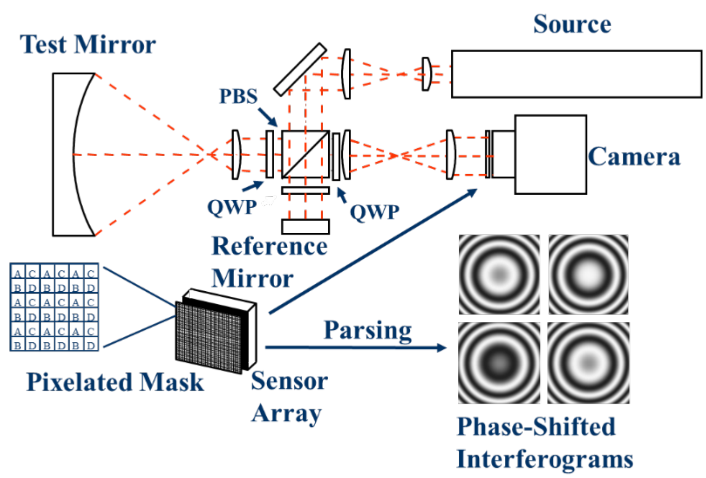

Fig. 18. Twyman-Green polarization-based interferometer adapted for simultaneous phase-shifting technology with pixelated mask. Adapted from Ref. [39].

4D Technology served as the primary metrology vendor for testing of optical and structural components for the James Webb Space Telescope (JWST). Their multi-wavelength interferometer made for testing the JWST operated with a 100µs exposure time, synthetic wavelength of 10mm, with accuracies of λ/50. [40]. Another of Jim's PhD students, Babak Saif, PhD

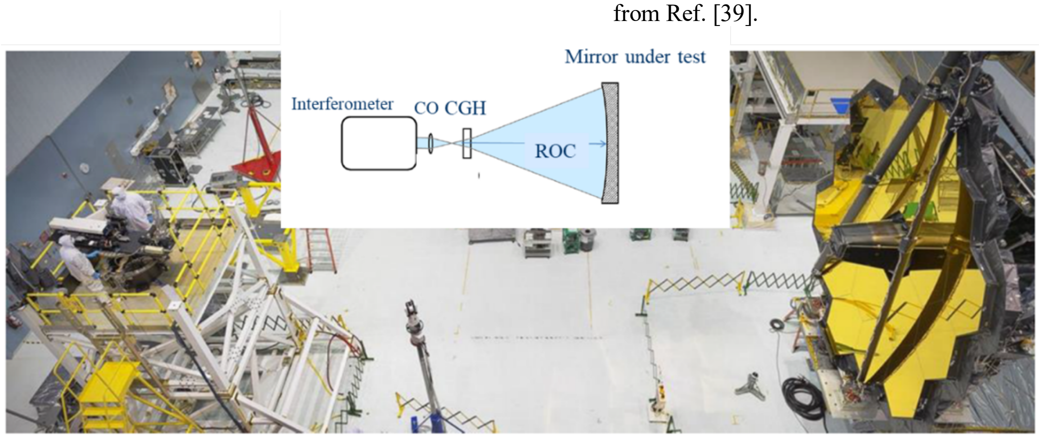

Fig. 19. Radius of curvature testing of the JWST [8].

2004, worked together with 4D to apply Electronic Speckle Pattern Interferometer (ESPI) to pixelated phase-shifting technology to measure the stability of the backplane of the JWST, a 1m target at a distance of 4m, on unisolated tables [41]. Additionally, there was another high-speed custom interferometer utilizing simultaneous phase-shifting applied to measure the JWST primary segments at the center of curvature at 5000fps [42]. See Fig. 19.

On the smaller scale, surface measurement with Linnik- and Michelson-based interferometers and low-coherence sources were adapted for snapshot/simultaneous use. One such system was designed by Joshua Wiersma, PhD 2012, who adapted the technology for a vertical scanning interferometer system using a PZT for extended-range measurement as shown in Fig. 20. [43, 44]

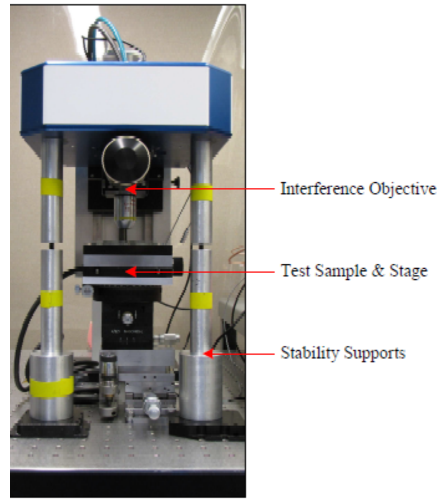

Fig. 20. Vertical scanning interferometry system built for extended range, vibration-insensitive measurements [15].

Linnik- based interferometers were used to expand the application range of interferometry into biology. A schematic of a system built for this purpose is shown in Fig. 22. It consisted of a polarization-based Linnik microscope with simultaneous phase-shifting accomplished with a pixelated phase mask. This system was used to visualize the short time-scale motion of primitive life and single-celled organisms, such as the protozoa in Fig. 22, and time-series of breast cancer cells responding to exposure to a compound in Fig. 23.

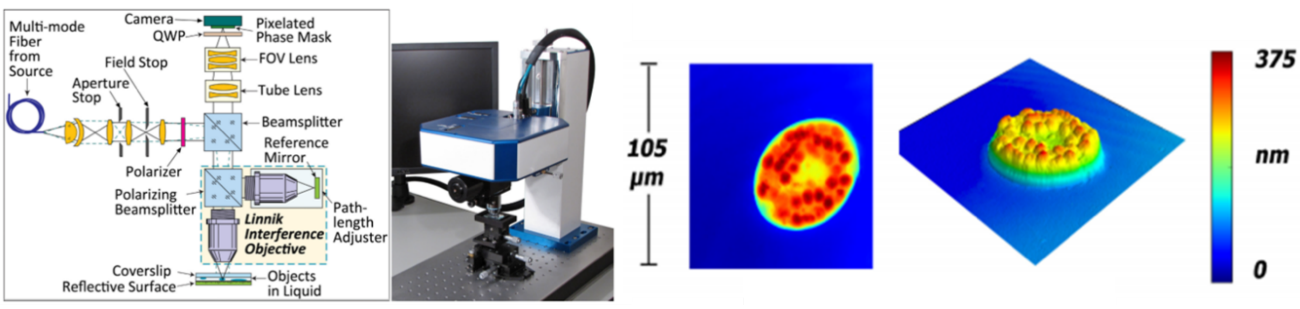

Fig. 22. (left) Optical schematic and (center) photograph of dynamic interference microscope. (Right) Images show optical thickness maps of protozoa from pixelated phase data [9].

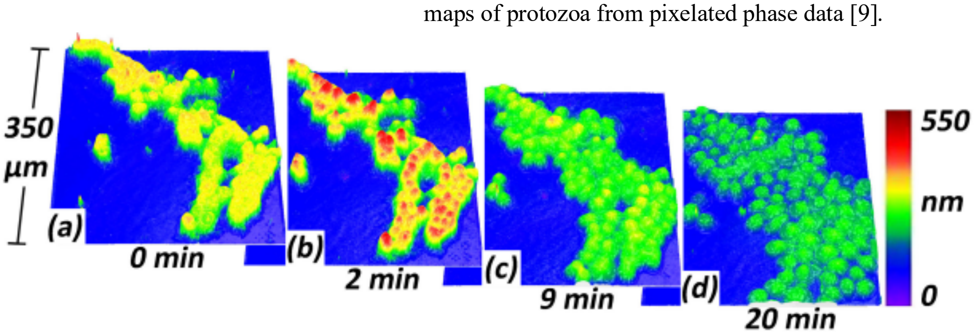

Fig. 23. Time series of 3D phase images of breast cancer cell culture taken at 20X. Through the time series, the cells begin to break down after exposure to NaOH [9].

Simultaneous phase-shifting has broken out of the nm-scale with one of the final new products developed while Jim was Chairman at 4D. A handheld simultaneous phase-shifting fringe projection system was designed and marketed towards shop floor measurements where fine features and defects are measured on the micron-scale (see Fig. 21).[45]

Fig. 21. 4D Inspec, a handheld vibration-immune metrology system for quantification of fine-scale features in manufacturing environments [18].

Through these contributions, James Wyant has inspired a generation of scientists and engineers who like him, see fringes everywhere.

6. LEGACY

In this paper, we have presented a quasi-chronological historical review of James C. Wyant's contributions to optical metrology and their impact on current technology. What has been obtainable has always been driven by the latest technology, and past inventions help to spur on new innovations as they are combined with the latest and newest technological advances. Thanks to much of the pioneering work of Wyant, his students, and all who have worked with him, highly precise and repeatable measurements are a matter of everyday business that help create much higher quality and more complex optics in much less time than when Jim began his career more than 50 years ago. As time has marched on, much of what was cutting edge research is now what we think of as simple, mundane optical testing. That these technologies can also be further applied to many more now unforeseen applications is left unspoken for now. They will reveal themselves as they evolve from what we now know as normal into new and exciting solutions for generations to come.

Contributing to that legacy has made it fun for all of us in this field. The person who helped to enable much of this legacy will remain a humble figure to us. To us, he will simply be Jim. May we all continue to see "fringes" everywhere in everything.

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