

Adaptive Optical Components

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Adaptive optics has recently been thrust onto the international scene by the successes reported by the European Southern Observatory and by the problems associated with the Hubble Space Telescope. This special issue is dedicated to adaptive optical components, specifically the deformable mirror and the wavefront sensor, which when combined with a control system offer the capability to provide real-time, closed loop correction of the optical wavefront.

The first two papers address the system aspects of an adaptive optic system. They are included to provide the reader with background information, describing the parameters of importance and the theoretical performance limitations. The first paper, by Robert Tyson, reduces the atmospheric compensation task to a few approximate expressions and provides relevant scaling laws. The paper examines the deformable mirror fitting error in terms of the mirror influence function and actuator geometry. Analytical results show that a multiplicative conversion factor of 1.06 should be applied to the actuator spacing when conducting the spatial filter performance analysis. The second paper, by Nicolas Roddier, describes an algorithm that simulates atmospherically induced distortions by using a Zernike expansion of randomly weighted Karhunen-Loève functions. The performance of adaptive optics systems is then evaluated in terms of the structure function and Strehl ratio by computer analysis.

The six papers that follow focus on the wavefront correcting element, the deformable mirror. The paper by Bill Hulburd and David Sandler describes the use of a segmented mirror as the wavefront corrector in atmospheric compensation systems. The operating principles, the effect of segment gaps, and the fitting error are described for the segmented mirror system. A technique is also described that uses absolute phasing of the segments for operation in a white light system. The paper by Jose Sasian describes the analysis conducted on a plane symmetric, four-mirror optical system that has a real pupil to accomplish passive or active wavefront compensation. The concept of upgrading a low quality, large optical system by active pupil wavefront correction is attained by using a small mirror located at the real pupil instead of an expensive deformable primary mirror. It is proposed that such a system may represent a cost-effective alternative for the construction of a large telescope. The fifth paper is by Mark Ealey and John Washeba. It describes the evolution of deformable mirrors that incorporate electroceramic actuators and continuous thin facesheets. A transition from piezoelectric actuators to those made from lead magnesium niobate (PMN) is described in terms of performance improvements. Technology trends toward increased packing density and compatibility with liquid cooling are briefly summarized. Deformable mirror performance is given for standard design configurations in terms of optical surface parameters.

In the sixth paper, Charles Swift, Erlan Bliss, David Lenz, and Richard Miller describe a deformable mirror developed to correct thermally induced aberrations in a solid state laser system. The mirror functions as an intracavity element and uses piezoelectric bonding moment actuators. Mirror surface measurements such as coupling coefficients and surface contour are in excellent agreement with finite element analysis. Brent Backhaus and Steven Forman then describe the development of metallic sandwich mirrors that are deformed by independently pressurizing cells within the core structure. The experiments and finite element models are described and results provided that establish that a spatially variable pressure distribution can be an effective method for deforming the optical surface. The paper by Pravin Mehta describes the development of a flat circular deformable mirror that incorporates diametral arrays of radial actuators to effect controlled deformation of the optical surface. The moment actuator is contrasted to the conventional piston type, and a closed form mathematical solution that describes the moment influence function is developed. A comparison between a Nastran finite element analysis and closed form solution based calculations shows excellent agreement.

The next three papers explore the wavefront sensor component options. The paper by Bruce Horwitz reviews the principles of operation of the grating based shearing interferometer. The temporal frequency and spatial frequency multiplexing techniques are discussed and hardware examples provided. It is shown that multiplexing techniques extend the applicability of the shearing interferometry. Spatial frequency multiplexing is useful for systems that require a very large number of subapertures, while temporal frequency multiplexing is most applicable when size, weight, and precision are critical considerations. In the tenth paper, Carl Witthoft describes the fundamentals of applying the Hartmann test to measure the phase errors necessary to perform optical wavefront correction. A theoretical treatment of wavefront sensor performance with and without image intensification is given. Results of both simulation and experiment illustrate improved system performance in terms of tilt dynamic range and reduced electronics noise. The eleventh paper, by François Roddier, explores the possibilities of providing improved Hartmann wavefront sensor performance through practical modifications. Fourier analysis techniques and associated Hartmann masks are discussed in terms of their interferometric properties. A differential Hartmann technique is proposed that provides improved dynamic range, accuracy, and spatial resolution as compared to classical Hartmann wavefront sensing techniques.

The final paper provides a novel method for optical processing in adaptive filters. In it, Gordon Anderson, Francis Kub, Rebecca Grant, Nicolas Papanicolaou, John Modolo, and Douglas Brown describe the first demonstration of acousto-optical excision using a GaAs photodetector array. The potential for application of the excision technique for performing multiplication functions in optical circuits and adaptive filters is presented.

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of scientists who have worked and contributed in the adaptive optics field but have not received their due recognition. My personal thanks to Bob, Larry, Jim, Joe, Ron, Ralph, and Dick for their personal support and mentoring.

I especially want to thank John W. Hardy, one of the founding fathers of the field of adaptive optics, and I dedicate this issue to him.

John was born in Bedford, England, in 1926. He graduated from London University in 1946 with a B.Sc. (engineering) degree, specializing in telecommunications. He then spent a few years in the British Army as a wireless officer in the Royal Corps of Signals, mostly in Berlin and Hamburg. In 1949 he joined Automatic Telephone and Electric Company in Liverpool, where he designed telephone transmission equipment. He transferred to ATE's Research Laboratory in 1954, where he had much more fun developing specialized test equipment for coaxial data transmission systems, published his first paper, and obtained his first patent. In search of wider horizons, he joined Westinghouse Electronics Division in Baltimore, Maryland, as a senior engineer in 1956, working on high-speed data transmission systems.



In the 1960s New England beckoned and he moved to Hermes Electronics in Cambridge, Massachusetts, which was run by a bunch of MIT whiz kids whose main products were precision time standards, crystal filters, and communication equipment. Shortly thereafter, the whiz kids sold out to Itek Corp. John transferred to the parent company, where he was promised interesting and challenging work. This proved to be an understatement. Coherent optical processing and holography were just being developed, and John's familiarity with (electronic) signal processing theory made the transition to optical processing an easy one. He worked on image transformation systems (both optical and electronic) to allow stereo viewing of distorted panoramic aerial photography. This was followed by the development of real-time image correlators for automated ortho-photo production.

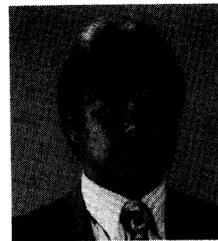
In 1970, John worked on early concepts for the GEODSS space surveillance system, which involved finding, tracking, and identifying orbiting objects. In 1972, DARPA was concerned with the problem of imaging space objects through the earth's atmosphere. Computer processing of the degraded images had been unsuccessful and better technology was required. However, the problems were formidable. Adaptive optics had been used to compensate coherent laser beams (using the COAT multidither technique), but this technique could not be used for passive imaging of distant extended objects. Wavefront sensors then in common use employed fringe analysis, which required several hours per frame. This time would have to be reduced by a factor of at least 1 million in order to compensate atmospheric turbulence in real time. Primitive segmented mirrors had been made but these were unstable and operated on coherent light with only $\pm 1/2$ wave of optical correction. Then there was the huge amount of computation to be done in real time—a roomful of computers would have been required.

To make a long story short, a system was proposed using a new type of shearing interferometer (invented by James Wyant) that used a moving grating, together with a set of parallel detectors and an analog data processor. The wavefront corrector was originally an electro-optical crystal. DARPA funded a program to demonstrate this concept in 1973. A better wavefront corrector (the Monolithic Piezoelectric Mirror) was developed in time for the first system tests in December 1973. This was the 21-channel Real-Time Atmospheric Compensation (RTAC) system, which is the prototype of many adaptive optics systems still in use today. John gave many papers and was awarded several basic patents on this system, which has stood the test of time. The Compensated Imaging System, whose performance is still classified, uses the same basic technology. This system has been in continuous operation since 1982.

In the mid-1980s the primary interest in adaptive optics was in laser beam compensation systems, which are often pulsed. In 1984, John developed a new adaptive optics system employing asynchronous pulse detection, using a self-scanned detector and all-digital data processing. Another recent project was the Integrated Wavefront Sensor, which laid the groundwork for a complete "adaptive optics system on a chip."

Over the years, one of John's main activities has been to "spread the word" on adaptive optics, especially to astronomers. This has involved numerous technical papers and talks to many different organizations, in this country and overseas. He has found it particularly rewarding to see that the European Southern Observatory is incorporating adaptive optics in their new telescopes and noticing results that John himself had seen during those first developmental years.

John, I dedicate this issue to you for your accomplishments, energies, and positive influences on others, including me. Enjoy your retirement John, and thanks from the many.



Mark A. Ealey received a BS degree in electrical engineering from the University of Tennessee in 1982. From 1978 to 1980 he worked as a junior engineer in the Atmospheric and Environmental Sciences Division at the NASA Langley Research Center in Hampton, Va., working on CO₂ and Nd:YAG lidar systems. In 1982 he joined United Technologies Optical Systems as an advanced systems engineer and served as a principal investigator with research and development tasks in novel ferroic displacement actuators, cooled deformable mirrors, and optical

sensors. In 1988 he began his work at Litton/Itek Optical Systems in the position of staff optical engineer. Currently, he is chief engineer and principal investigator responsible for research and development of advanced adaptive optic systems and cooled beam control components, both passive and active. He is the author of more than 40 journal, conference, and technical publications and holds several patents in the fields of adaptive optics, cooled active and passive mirrors, optical sensors, and ferroic and nonlinear optical materials. He is a member of SPIE, the OSA, and the IEEE.