AOIM

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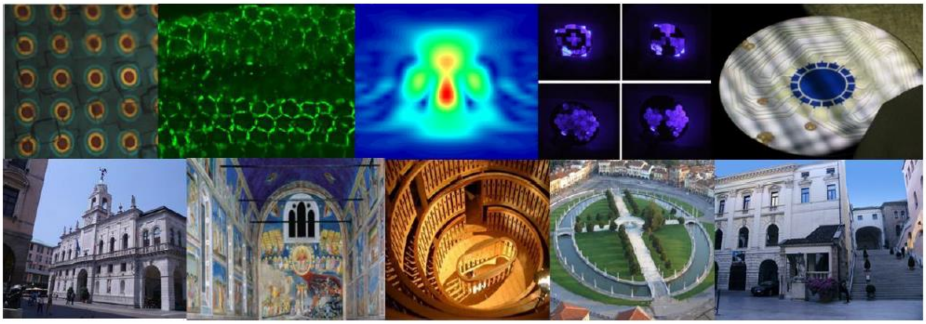

AOIM15 abstract Book
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Ophthalmology

Invited talk:
Wavefront sensorless adaptive optics optical coherence tomography for retinal imaging in mice and in humans

Marinko Sarunic

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We present our work on wavefront sensorless adaptive optics optical coherence tomography (WSAO-OCT) as a technique for in vivo high-resolution depth-resolved imaging that mitigates some of the challenges encountered with use of wavefront sensors. In WSAO-OCT, the Hartmann Shack wavefront sensor is replaced by a depth-resolved image-driven optimization algorithm, with the metric based on the OCT volumes acquired in real-time. A high-speed GPU processing platform and fast modal optimization algorithm was developed for real-time, in vivo retinal imaging. Image quality improvements with WSAO OCT are presented for both pigmented and albino mouse retinal data. We also describe WSAO-OCT for imaging the human photoreceptor mosaic in vivo at several eccentricities, and demonstrate the improvement in photoreceptor visibility with WSAO aberration correction.

Optimal template location for retinal motion extraction using cross-correlation with a line scanning ophthalmoscope

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The human eye continually moves even when we steadily fix our gaze on an object [1]. For many decades, cross-correlation has been the most widely used method for retinal motion extraction, and cross-correlation involves computing image intensities to maximize similarities between a pair of discrete rectangular images so that template location of the cross-correlation are related to detection accuracy[2,3].
In this study, we extended previous studies by rigorously evaluating the performance of cross-correlations to extract retinal motion. Correlation templates of different retinal features were used to determine the optimal template for retinal structures. We can draw a clear conclusion. The template employing distinct retinal vessels had the highest accuracy and stability, and characteristics of blood features are the best potential templates in the cross-correlation algorithm. The vascular pattern of the retina should

be used as the main template cue for cross-correlation extraction of retinal motion. The essential reason is that the retinal background is fairly uniform, and vessels are shown very distinctly. Ordinarily, a variety of vessel bifurcation structures appear in retinal imaging sessions. As a result, vessel bifurcation or vessel features occupying approximately eight percent of the template area, which simultaneously has a non-uniform intensity distribution, are the optimal targets in cross-correlation templates for retinal motion estimations.

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Progress on developing multimodal Adaptive Optics based in vivo small animal retinal imaging systems

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We present our progress on developing Adaptive Optics enhanced multimodal mouse retinal imaging systems including stand alone, and combination of Fourier domain optical coherence tomography (FD-OCT) and Scanning Laser Ophthalmoscopy (SLO) systems. Combination of OCT with SLO allows for simultaneous detection of structural (back reflected light) and potentially functional (fluorescently emitted light) signals [1-2]. We evaluated two ways of correcting ocular aberrations in the mouse eye. First one by using "classical" Wavefront Sensor (SH-WFS) and and a high-speed, high-stroke deformable mirror (DM): (DM-97-15; ALPAO SAS) based AO correction and second implementing a wavefront sensorless Adaptive Optics (WSAO) scheme utilizing the MEMS based tip-tilt DM: (PTT111; IrisAO Inc.) and intensity of en face images acquired by FD-OCT as a correction metric [3-4]. Optical design requirements of both wavefront correction approaches will be compared and discussed. Several imaging results of retinal microscopic structures acquired from retinas of several different mice strains will be provided and cross platform imaging results will be compared. Finally example application of our AO instrumentation to study animal models of human eye disease will be provided.

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Microscope-integrated optical coherence tomography with a head-up display for glaucoma surgery

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This article reports a real time, high speed swept source optical coherence tomography (SS-OCT) with 1310nm light source for the image guidance of glaucoma surgery. A SS-OCT and a microscope was integrated to image the surface and the tomography of the anterior segment in real time, making the anterior surgery become more visualized and more precise. A two graphics process units (GPUs) architecture was adopted to speed up the data processing and real time three dimension volumetric rendering. A Google glass was adopted as co-monitor to show the region of interested during surgical maneuvers, which can reduce the optical system's complexity. Finally, experiments were underwent to verify this integrated system.

High resolution imaging using adaptive optics assisted SLO/ OCT

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In this study we demonstrate the capabilities of an adaptive optics (AO) scanning laser ophthalmoscope (SLO)/ optical coherence tomography (OCT) instrument for retinal high resolution imaging. AO-SLO and AO-OCT images are recorded simultaneously with a pixel to pixel correspondence. Thereby a direct comparison between both imaging modalities becomes possible. One key factor of the system is an implemented active axial eye tracking for the OCT channel. This allows for fast recording of en-face OCT images with

reduced motion artifacts. In addition time resolved measurements of retinal blood flow or frame averaging (for increased image quality) becomes possible. Finally, the system is equipped with a dynamic focus scheme which allows the maintenance of the high transverse resolution throughout the entire imaging depth.

Vision

Invited talk:

How can we get several billion people in the world to see with 20/20 Vision?

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A consensus is beginning to emerge that between two and three billion people in the world need corrective eyewear if they are to see as clearly as possible. Whilst one solution to this problem is to provide them with conventional eyeglasses to correct their refractive error, that turns out to be impossible to achieve without training a very large number of optometrists , and putting in place a large infrastructure, something which would be both expensive and lengthy.

An alternative approach is to take advantage of the fact that everyone has an eye-brain adaptive optical system which has evolved over time to function very well. If a wearer is equipped with eyeglasses with simple lenses whose focus can be easily changed manually, then the wearer can effectively " piggy-back" on their own eye-brain adaptive optical system to find best focus, and thereby correct their own refractive error with such glasses. Our clinical research has shown that this approach can work extremely well, as I will explain. Several challenges remain, and I will suggest how they might be dealt with.

A fractal eye model to predict the wide-angle PSF

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The optical quality of the retinal images in the eye is influenced by aberrations and intraocular scattering [1]. While aberrations affects to the central part of point spread function (PSF), intraocular scattering produce a wide-angle halo. In most eyes, aberrations can be well approximated using Zernike polynomials up to the 4th or 6th order indicating characteristic sizes in the phase map on the scale of one millimeter. In the other hand, light scattering has its origin at the interaction of light with significantly smaller features such as cell nuclei and protein aggregates that have characteristic sizes on the scale of micrometers.

Adaptive Optics (AO) provide well established approaches for the correction of ocular aberrations [2]. In order to extend AO for the compensation of higher spatial frequencies, related to intraocular scatter, a wide angle description of the wide-angle PSF would be required. In that context, we have developed an eye model based on fractal surfaces, which is capable to replicate simultaneously the effects of both aberrations and light scatter according to the wide-angle PSF of the CIE (Commission International d'Eclarairage) standards [3]. The model accurately reproduces the increase of scattering associated with the age. Numerical simulations and experimental results obtained with a Liquid crystal on Silicon (LCoS) Spatial Light Modulator (SLM) will be presented.

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Advanced Eye Refraction and Visual Testing with Liquid Crystal-based Adaptive Optics Technology

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The incorporation of adaptive optics (AO) technology in ophthalmic instruments permits to obtain and use optimized advanced refractions, beyond defocus and astigmatism. With this technology, patients can evaluate in advance customized optical solutions, offering the possibility to choose the most suitable alternative for vision correction. Among others, those can include refractive or diffractive multifocal profiles and aspheric monovision. In this context, a new AO system will be presented with enhanced capabilities for visual testing and advanced refraction. The experimental set-up incorporates a fluidic lens for the control and/or correction of defocus, in combination with a liquid crystal on silicon (LCoS) phase modulator for the manipulation of the rest of eye's aberrations. A motorized diaphragm acting as the exit pupil assured full control of optical conditions during the evaluation of vision. An OLED micro-display in the stimuli enabled to perform different visual tests in white light simultaneously to the manipulation of ocular aberrations. Those were measured by a Hartmann-Shack wavefront sensor operating in IR light. The set-up was successfully demonstrated in real patients. Some examples of vision through customized profiles in normal eyes will be presented. The incorporation of a fluidic lens in the system significantly increases phase modulation performance. With these new features, the instrument significantly expanded the range of population that can evaluate, covering many cases of pathological eyes.

Adaptive Optics for Contact Lens Evaluation

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Higher order aberrations in the eye can be corrected with soft contact lenses. Certain amounts of spherical aberration, when induced on the contact lens, have been shown to improve visual acuity [1]. Custom contact lenses for subjects with keratoconus have also been shown to improve vision [2]. We are in the final stages of building an adaptive optics system that can simulate the effect of a soft contact lens. Most importantly, the simulation includes the translation and rotation of the contact lens on the cornea. The contact lens is simulated by the combination of a badal system and deformable mirror, while the subject evaluates the performance of the contact lens subjectively. We will present work on the building of the contact lens simulator and the evaluation with a Shack-Hartmann wavefront sensor (SHWFS). The SHWFS is positioned in the place of the human eye and verifies that the contact lens can be accurately simulated. The tolerance for the eye's position is evaluated. The proposed system offers an effective method to test several different contact lens designs on an individual subject. This is an important improvement in the evaluation of customized contact lenses because the translation and rotation of the contact lens on the cornea makes it difficult to derive the best contact lens design [3]. By eliminating the need to manufacture a proposed design, a more efficient and reliable method for evaluating customized contact lenses is developed.

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Laser + turbulence

Applications of adaptive fiber optics collimators for laser beam combining and propagation through atmosphere turbulence

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The most recent progress on the design of adaptive fiber optics collimators (AFOCs) and its applications in laser beam combining and laser propagation through atmosphere turbulence were reported, all in the Key Laboratory on Adaptive Optics (KLAO), Chinese Academy of Sciences (CAS). The theoretical model of the AFOC was established. Methods to improve the resonance frequency and control bandwidth of AFOC were discussed. A tip/tilt range of near 100 micro-rad with the first resonance frequency of over 2000 Hz was achieved. The stochastic parallel gradient descent (SPGD) algorithm was employed as the control strategy of single AFOC and AFOC array for phase-locking and tip/tilt control in close loop. The systems and the experiments results of coherent and incoherent beam combining of fiber lasers, and the applications of this technology for free-space optical laser communication and laser propagation through atmosphere turbulence have been demonstrated. It is showed that the AFOC can be used both for launching fiber lasers and for receiving the lasers from remote beacon, and the AFOC is suitable for the applications in beam combining of fiber lasers and the laser propagation through atmosphere turbulence.

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Atmospheric Distortion of Multichannel Laser Radiation and Correction for Distortion

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The results of numeric simulation are presented in the report of multichannel laser radiation propagation under conditions of free diffraction and in a turbulent

atmosphere.
It was shown that in free space a multichannel system allows one to obtain higher concentration (20-50%) of radiation energy on the object comparing with a Gaussian beam. Dependence of the power-in-the-bucket parameter on the path length has well-pronounced maximum the height of which depends on density of aperture filling by optical fibers and on number of fibers.
Intensity of atmospheric distortion decreases with increase of the number of channels. Adaptive correction for turbulent distortions results in two-times increase of energy concentration for systems with 9 and 81 channels. For systems with greater number of channels (201 channels) the results of correction do not depend on turbulence intensity.

Dynamic properties of adaptive optics systems

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Modern adaptive optical systems are dynamic systems with feedback, and are characterized as systems with constant time delay [1]. Uncertainty of atmospheric turbulence, which manifests itself in the form of fast changes of its parameters, makes it necessary to develop adaptive optical systems using statistical prediction of random phase fluctuations.The time delay of the adaptive optical system consists from the information processing time, computation time of the adaptive mirror instructions and time which depends on the inertial and transient mechanical features of the active mirror. This problem can be solved using the method of advanced adaptive correction [2], the essence of which is applied to the mirror instructions calculated relative from the wavefronts measured in previous times. This approach involves the making of the prediction changes in the wavefront for a time. However, this method does not take into account the measurement error of the wavefront and the prediction wavefront error. To eliminate errors in the synthesis of statistically-optimal control algorithms for deformable mirror can be applied, for example, Kalman filter. To construct these algorithms required to build a model of the evolution of the system. The main parameters responsible for the evolution of the atmospheric optical system are wind velocity and structure characteristic of refractive index fluctuations. The calculation of the transverse components of wind velocity and structure characteristic of refractive index fluctuations is based on the use again [3, 4] the data which obtained from Shack-Hartmann sensor.

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Fiber optic gyroscopes based on photonic crystal fibers

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Fiber-optic gyroscope is one of the applications of optical fibers dependent mainly on the Sagnaceffect . It is of important applications in the field of space navigation . Photonic crystal fiber gyroscopesare a kind of optics gyroscopes that present a diversity of new and impr oved features beyond whatconventional optical fiber gyroscopes can offer . In this paper we proposed to use of a photonic crystalfiber with an inner hollow defect. The use of such fibers is not affected by a material medium on thepropagation of optical radiation. Photonic crystal fibers present special properties and capabilities thatlead to an outstanding potential for sensing applications .

Artificial Atmospheric Beamlet as a Test-Bed for Adaptive Optics

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The in-door free atmosphere path with the total length up to 700 m [1,2] provides the unique capabilities for testing optical systems in the stable, controlled and repeatable atmospheric conditions. We present and discuss the results of experimental investigation of Shack-Hartmann wavefront sensing and closed loop adaptive optics correction of atmospheric distortions at this beamlet. It was shown that under stable conditions (without heating and artificial wind) the distortions, accumulated along the path, have the magnitude of 1-2 microns (peak-to-value) and are rather slow. The use of closed-loop adaptive optical compensation in a single-mirror (flexible mirror diameter 50 mm; no tip-tilt correction) configuration [3,4] provided complete correction of these distortions down to diffraction limited performance. So our first experiments has confirmed the expectations that out beamlet can be used in future as a rather convenient test-bed for various adaptive optical systems' investigations and characterization with the rather "soft" starting conditions.

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Low Cost Adaptive Optics Testbed for Small Aperture Telescopes

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We present here a significant achievement of a low cost and compact Adaptive Optics (AO) system that could be valuable for the broad astronomy community, including amateur astronomy. An opto-mechanical testbed was developed and fitted to a 16" telescope and to a 1-m class telescope, with the AO control fully implemented in a low cost FPGA. An optimized centroiding algorithm based in the Fourier transform is implemented, and laboratory and on-sky tests in the 16" telescope are described.

Numerical Simulation of LGS Propagation and Extended Spot Effect in Adaptive Optics for Atmospheric Turbulence Correction

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Laser Guide Star (LGS) is an artificial turbulence-probing source of Adaptive Optics (AO) for compensating for wave-front error of the interested object, and for realizing an ideal resolution recovery in atmosphere. Actually, elongation phenomenon of the LGS Hartmann spots comes with the off-axis projected beacon laser beam lighting up the specific depth and altitude location of LGS backscatter region in the atmospheric layer, which will have an influence on centroid measurement accuracy in Hartmann apertures, and will lead to non-ideal wave-front distortion compensation. In this paper, a numerical model for describing the LGS up- and downward propagation through atmospheric turbulence has been built up and focused on sodium LGS. By modeling of multiple random phase screens along the LGS propagation path including 30km turbulence effect, and multiple sub-layers at different altitudes in the mesospheric sodium layer with H_{Na}=90km mean altitude, the Na LGS intensity variations with time at sodium layer have been represented, and the characteristics of short-exposure elongated Na LGS spots on the Hartmann wave-front sensor (WFS) for a 3m telescope model have been studied. At last, in order to investigate the LGS elongation impact on wave-front measurement accuracy with WFS, the model has been integrated with our previous LGS anisoplanatism numerical model [1], and provides information about the Zernike-modal decomposition difference of the reconstructed wave-front between the point source and the elongated

source for sodium LGS.

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Wavefront sensor

Invited talk

Large and extremely large: Field of View and telescope sizes in AO for Astronomy

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The narrow Field of View of AO systems in Astronomy is one (among with complexity and sky coverage) of the main operational limiting factors. With the advent of the large (i.e. 8 to 10m class) telescopes and the coming era of extremely large telescopes (in the 20 to 40m range of diameter) the quest for a larger Field of View becomes more and more relevant. I describe the past and current efforts in wide field AO systems in astronomy and the ongoing developments for a new paradigm, where the sensed Field of View is going to surpass the scientifically usable Field of View in order to give access to diffraction limited capabilities with a sky coverage approaching the whole celestial sphere.

Holographic Wavefront Sensors

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The review paper considers and compares various proposed and realized schematics of holographic wavefront sensors (WFS), including traditional WFS with holographic optics, modal WFS with holographic filtration of Zernike polynomials [1-4], similar techniques in their application to the zonal WFS and also some other techniques (Talbot WFS [5], polarization holography WFS [6] etc.). We consider the limitations, imposed onto holographic WFS performance by the use of straight-forward holographic technique and possible improvements, which can be obtained by the use of more advanced techniques.

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Realization of an analogue holographic wavefront sensor

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Adaptive optics (AO) is used to compensate environmental influences on the propagation of (laser) light. Applications at Fraunhofer IOSB include laser communications and directed energy. For scenarios involving moving platforms or targets, the traditional approaches fail because of insufficient measurement speed and because well-established wavefront sensors are all sensitive to scintillation [1].
For measuring the wavefront deformation of a laser beam the Holographic Wavefront Sensor (HWFS) is a promising alternative to currently used methods [2-5]. Here the wavefront of the incoming beam is decomposed into its aberrations by the diffraction process. After the readout of a detection device, this information can be used to control a modal corrector (e.g. deformable mirror) in a closed-loop AO system. Besides the high measurement speed, the sensor is in principle insensitive to scintillation.
We realized HWFS by recording an analog multiplex hologram. We analyzed the sensor response to incoming laser beams with defined wavefront aberrations. We are now working on integration of the HWFS in an AO system. In the field of laser communications this can lead to optimized fiber coupling and with this to higher bandwidths and a better light efficiency.

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Liquid-filled photonic crystal fiber as wavefront sensor

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A photonic crystal fibre filled with castor oil (LF-PCF) has been used as a waveguide-based wavefront sensor. The high-index columns of oil in the PCF form an array where each one will act as a waveguide [1-3]. The sensing method makes use of the angular-dependent light-coupling efficiency caused by a wavefront gradient at the entrance aperture in such a way that the coupled light power to each waveguide is influenced by aberrations in the entrance pupil [4]. Measurements have been realized using a HeNe laser as an illumination source and a deformable mirror (D-M) conjugated to the entrance face of the LF-PCF to generate well-controlled optical aberrations at the LF-PCF plane. The light power coupled to each waveguide of the LF-PCF has been analyzed for tilt, defocus, astigmatism and coma. Measurements show that the coupled power in the oil-columns of a LF-PCF is sensitive to local tilt of the wavefront, with fair agreement with simulations. This demonstrates that a LF-PCF has significant potential as a wavefront sensor with possibilities to overcome some intrinsic problems of the Hartmann-Shack such as the wavefront sensing in diminutive spaces. Wavefront reconstruction algorithms and new designs will be implemented in the future.

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Improved Thresholding and Ordering for Shack-Hartmann wavefront sensors implemented on an FPGA

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We present improvements for a recently introduced real-time image processing approach [1] of a Shack-Hartmann wavefront sensor (SHWFS) using a Field Programmable Gate Array (FPGA). The approach, based on connected-component labeling (CCL) and subsequent ordering, shows higher-range when compared with the standard approach while being deterministic and real-time capable. However, intensive experimental tests have revealed some issues, e.g. due to unequal spot intensities that originate from the typical Gaussian intensity profile of the beam and ordering problems that are due to intensity changes resulting in newly detected spots. To tackle these issues, we here propose improvements on thresholding and ordering. These changes have been simulated first with MATLAB before being implemented in VHDL on an FPGA. The algorithms have been designed in such a way that their impact on the latency of the evaluation is minimized and the implementation on an FPGA is efficient.

In this paper we demonstrate that the developed algorithms are competitive with those in commercial SHWFS's, the latter showing much slower performance. The improved evaluation performance given in our approach, however, just requires standard techniques from image processing in order to adopt CCL to the problem in a simple way. With our public-open algorithm, the performance and accuracy of the sensor may easily be judged. Concerning performance the algorithm shows to be at least equivalent with the non-published, commercial algorithms.

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Fourier phase unwrapping in a digital phase shifting point diffraction interferometer

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The use of a spatial light modulator as phase-shifting point diffraction interferometer was demonstrated recently for wavefront sensing applications [1]. In addition to achieving phase shifting without the need for mechanically moving parts, it allows tunability in fringe spacing by altering the spacing between the partially transmitting pinhole masks generated by the spatial light modulator. Wavefront phase can be retrieved from a linear combination of the phase-shifted interferograms [1]. However, it was noted that a small amount of detector or scatter noise could affect the accuracy of the wavefront sensing. Here, a Fourier-based phase unwrapping method was used to reconstruct the wavefronts from the interferograms [2]. It was observed that the rewrapping of the Fourier reconstructed wavefronts resulted in phase maps that matched well the original wrapped phase obtained from the interferograms and its performance was more stable and accurate than conventional unwrapping.

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Measuring the wavefront and phase of structured light with spatial light modulators

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Wavefront and phase measurements are traditionally performed with devices that either consider local gradients on the phase to infer the wavefront, or interfere the wave with a reference to note the fringe pattern and thereby reconstruct the wavefront. These tools do not work with vector beams and are problematic for vortex beams. Here we outline a simple tool for the measurement of vector-vortex beams in real time during propagation [1]. Our approach combines non-homogenous polarization optics and a spatial light modulator to perform all-digital wavefront sensing of the light. We show that when combined with modal decomposition of the light, any unknown beam can be measured with this tool. We compare our results to more standard approaches and show excellent agreement.

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Curvature sensing with a Shack-Hartmann sensor

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Shack-Hartmann (SH) sensor, based on sampling of wavefront tilts in subapertures, is a simple, reliable, and widely used in adaptive optics wavefront sensor. A wavefront curvature sensor has the advantage of providing the results suitable for direct control of membrane and bimorph deformable mirrors [1], but requires linear registration of intensity in two planes. SH sensor modifications using astigmatic microlens array [2] and three SH sensors [3] provide measurement both in the form of wavefront gradients and Laplacian curvatures. In this work, we consider a simple arrangement that turns a standard SH sensor into a curvature sensor by moving the camera chip of the SH sensor into the optical plane conjugated to a deformable mirror. This establishes a direct geometric correspondence between the coordinates on the DM surface and the sensor chip. Then, change in the local centroid density corresponds to the Laplacian curvature of the mirror, and the phase at the boundary can be found from the centroid displacements along the edge of the pupil. We investigate the feasibility of this approach for direct control of membrane deformable mirror by measuring the dependence of the calculated centroid density on the control signal applied to the mirror actuators. The experimental results demonstrate a good linear dependence.

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Intensity-based Wavefront Sensing employing Surface Plasmon Polaritons

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Wavefront sensing is commonly achieved by monitoring changes in propagation direction of ray components with respect to that of a corrected reference wave as used with the Hartmann-Shack (HS) and in interferometric methods [1]. Pupil intensities can be employed that allow subsequent wavefront determination as used in curvature and pyramidal sensors [1], and recently in the angular-dependent coupling efficiency to waveguide arrays [2] that sample an incident wavefront similar to the subaperture division of a HS. Here, we report on an intensity wavefront sensing method that makes use of attenuated total internal reflection (ATIR) for surface plasmonpolariton (SPP) excitation in a Kretschmann configuration at a planar metal-dielectric interface while also giving insight into contaminants at the interface [3,4]. The reflection has a narrow angular dependence that can be used to determine aberrations across an incident wavefront. The dynamical range and sensitivity is set by the material and illumination conditions. We show numerical results using ComsolMultiphysics® for thin Ag and Au films on glass and compare these to experimental results obtained with an adaptive optics (AO) kit (Thorlabs Inc.) for different Zernike aberration modes. The method is validated although complications remain to be overcome as only TM-polarized light can be analyzed for one prism setting and the needed elimination of print-through effects of the mirror used to generate controllable aberrations.

Least Squares Fitting of Hartmann or Shack-Hartmann Data with a Circular Array of Sampling Points

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A least squares procedure to find the tilts, curvature, astigmatism, coma and triangular astigmatism by means of measurements of the transverse aberrations, using a Hartmann or Shack-Hartmann test is described. The sampling points are distributed in a ring centered on the pupil of the optical system. The properties and characteristics of rings with three, four, five and six sampling points are analyzed with some detail.

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Wavefront Sensing and Analysis for Underwater Laser Propagation

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A series of experimental tests have been conducted to evaluate the benefit of using some form of Adaptive Optics to shape a laser beam that is propagating under water. The experiments were carried out at the NRL laboratory facility in Stennis, MS, where a large Plexiglas tank of water is equipped with heating and cooling plates that allow for a well measured thermal gradient that in turn generates different degrees of turbulence that can distort a propagating laser beam. In this paper we present an analysis of the wavefront measured in various conditions and derive statistical parameters from it. We also performed open and closed loop adaptive optics tests and we present some of the preliminary results.

Development of a CPU-based architecture for high performance adaptive optics systems

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A basic Adaptive Optics setup is composed of three key elements: a wavefront sensor to detect the aberrations; a deformable mirror to correct such aberrations; and a closed loop control system connecting both sensor and deformable mirror in order to reduce the aberrations.

The control system can be realized by the use of a dedicated platform such as an FPGA or GPU, because dedicated hardware can guarantee higher performances than software written for generic architecture such as CPU [1][2]. On the other hand, such solutions need more development time and hardware than a CPU-based approach, thus being more expensive both towards the developer and the end user. Moreover they are not flexible, operating on a strict selection of hardware. The proposed solution aims to be a cost-effective adaptive optics setup. It is a CPU-based approach that relies on Qt, which is a cross-platform application, and UI framework [3]. By using Qt Creator, an IDE specifically designed to work with Qt, the development effort is greatly reduced: it natively manages both code and GUI, and, given the required toolchains, it can be easily compiled in many different platforms, without source differentiation. The source is written and compiled in C++ language, so that it runs fast with minimum overhead from the Qt classes. We demonstrate that the system can operate in real time at more than 100Hz frequency.

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Wave-Front Sensing Library with CPU and GPU

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AO (Adaptive Optics) is composed of three parts. One is a sensor to measure wave-front known as Wave-Front Sensor (WFS), another is a corrector to reconstruct its aberration like DM (Deformable Mirror) and TTM (Tip-Tilt Mirror), and the other is a control system to analyze wave-front aberration and its reconstruction as well as to control the sensor and the corrector. The control system is a brain part of AO system, and it needs high performance in computation for wave-front analysis and reconstruction matrix. Generally we configure the control system in various ways with DSP, FPGA, CPU, or GPU. Nevertheless, we can construct relatively simple AO system in hardware with CPU or GPU. We can make a code and debug it in more efficient environment, because the simpler the system the better. We are developing a wave-front sensing library for Shack-Hartmann Wave-Front Sensor (SHWFS) type using parallel programing technology with CPU and GPU on Windows system. Basically it provides three algorithms for computations of sub-aperture displacements; centroid, sum of absolute differences (SAD) and FFT convolution. And it can compute Zernike Polynomial, subpixel accuracy displacement, histogram, contrast, and so on in parallel mode. Moreover we can display their information as an image. After optimization, we will apply this library to a simulation test-bed and a real-time AO system for astronomical purpose.

Hartmannometer vs Interferometer to measure optical elements – what is the best?

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In this paper we consider two approaches widely used in optical testing: Shack-Hartmann wavefront sensor (SHWFS) and Fizeau interferometer technique. Fizeau interferometer that is widely used in optical testing can be easily transformed to a device using SHWFS, the alternative technique to check optical components. We call this device Hartmannometer, and compare its features to those of Fizeau interferometer(FI).

Aberrations: Effect of the reference point

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Aberration is usually defined as the deformation of a Gaussian reference sphere, centered on a particular reference point. In adaptive optics we require to adjust the aberrations at the plane of the correction device, ideally with the tip/tilt and defocus terms omitted, as otherwise the system can be attracted to bright neighbouring image points. We first investigate the aberrations of a tilted dielectric plate. Different expressions are given in the literature for this simple case, which we attribute to differences in the definition of aberration, and choice of the reference point. This then leads to a new set of aberrations, analogous to the Zernike polynomials, that allow aberrations to be specified independent of a particular reference point.

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Control

Wavefront Sensorless Algorithms for Wavefront Correction in Model-Based OCT

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In a recent manuscript [1] a transfer function for wavefront aberrations in optical coherence tomography is proposed and validated. This model predicts the loss of the optical coherence tomography (OCT) signal caused by an arbitrary wavefront aberration expressed in Zernike polynomials. The model is developed both for reflector and scattering media. Several advanced optimization algorithms are tested and optimized on the OCT wavefront aberration model. Lower RMS wavefront errors are achieved with six to ten times less measurements when compared to a conventional coordinate-search algorithm.

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Feedforward Operation of a Lens Setup for Large Defocus and Astigmatism Correction

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In this manuscript, we present a lens setup for large defocus and astigmatism correction. A tunable defocus lens and two rotational cylindrical lenses are used to control the defocus and astigmatism. The setup is calibrated using a simple model that allows the calculation of the lens inputs so that a desired defocus and astigmatism are actuated on the eye. The RMS wavefront error of the desired defocus and astigmatisms is 0.169 diopters.

Discretized Aperture Mapping for high-contrast imaging

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Discretized Aperture Mapping (DAM) is a low-pass optical filter able to smooth an aberrated wavefront and to remove scattered light, improving the dynamic range in high-contrast imaging.

DAM is composed of an afocal double lenslet arrays, with an optical filter array in the intermediate focal plane. Each sub-beam is diaphragmed by a lens, focussed into an optical filter to become coherent in phase, and re-expanded onto another lens to produce a collimated filtered beam. While the sub-apertures become flat in phase, the differential phases between each pair of sub-apertures is passing. The whole aperture is no more a continuous wavefront but a discretized wavefront, with differential pistons between the sub-apertures. Consequently, DAM remains invariant by translation in the focal plane when pointing an off-axis object. First, the imaging properties of DAM preserves the object-image convolution relationship within a finite field of view. Second, the filtering properties of DAM improves the image quality by reducing the contribution of scattered light, by filtering out the high spatial frequency content of the incoming wavefront. We argue that DAM should be used as a low-pass spatial filter on any optical systems where the high spatial frequency content is useless and problematic.We hope that this new concept will open new research areas for direct imaging applications which require high dynamic range, like in astronomy (e.g. to image exoplanets) or in medicine (e.g. to image the eye retina).

Microscopy

Invited talk:

From stars to neurons – adaptive optical microscopy for deep brain imaging

Anderson Chen

Janelia Research Campus (USA)

Imaging neurons deep within the brain of a living mouse shares many similarities with gazing at distant stars with a telescope. In both cases, imaging quality is limited by optical aberration and scattering. Wavefront shaping using adaptive optics (AO) has revolutionized astronomy by allowing us to obtain sharp images of celestial objects through the turbulent atmosphere. Similar technology can be applied to microscopy for optically transparent samples but not mammalian brains, which are highly scattering. In this talk, I will describe our work to extend AO microscopy to these more optically challenging systems, which has allowed us to image both the input and output of mouse cerebral cortex with diffraction-limited resolution.

Invited talk:

Adaptive Optics in Microscopy

Martin Booth

University of Oxford (UK)

High resolution microscopy relies on the use of high quality optics with the goal of obtaining diffraction-limited operation, working at the physical limits imposed by the wavelength of the light. Yet in many cases this goal is not achieved as aberrations, distortions in the optical wavefront, blur the focus and reduce the resolution of the system. Aberrations can arise from imperfections in the optics, but are often introduced by the specimen, particularly when imaging thick specimens. One common source is a planar mismatch in refractive index, such as that between the microscope coverslip and the specimen mounting medium, which introduces spherical aberration. Biological specimens also exhibit variations in refractive index that arise from the three-dimensional nature of cells and tissue structures. In general, these aberrations become greater in magnitude and more complex in form as the focusing depth is increased. The induced wavefront aberrations distort the focus causing a reduction in resolution and, often more importantly, reduced signal level and contrast. These effects limit the observable part of the specimen to a region near the surface.

Adaptive optics systems enable the dynamic correction of aberrations through the reconfiguration of an adaptive optical element, for example a deformable mirror or liquid crystal spatial light modulator. Various adaptive schemes have been developed for a range of different modalities including confocal, multiphoton and widefield microscopes. Some systems employ wavefront sensors to measure aberrations, whereas others use indirect sensing to determine the wavefront distortions. We review the methods and applications of these systems in biological sciences and other areas. We also present recent developments in adaptive optical methods for super-resolution nanoscopy – methods through which resolutions far below the diffraction limit of the microscope are achieved through combinations of optical and photo-physical effects.

Multiphoton Imaging with Wavefront Sensorless Adaptive Optics

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Multiphoton microscopy is being used in all major areas of biomedical research. Exploiting its optical sectioning properties, high-resolution 3D images can be created. However, one of the limiting factors is the presence of specimen-induced aberrations. These affect both resolution and maximum depth of penetration. Since direct measurement of these aberrations is challenging, different approaches involving wavefront sensorless adaptive optics have been used to minimize these detrimental effects [1,2]. In particular, spherical aberration (SA) [3] and Bessel beams [4] have been reported to increase the depth-of-focus in multiphoton imaging of thick samples. Here, we propose a wavefront sensorless technique combining Bessel beams (generated by means of 0- phase masks (0PMs)) and SA patterns to improve the quality of multiphoton images. For that aim a Liquid-Crystal-on-Silicon spatial light modulator (LCoS-SLM) was implemented into a custom multiphoton microscope [3]. The LCoS-SLM was used to systematically generate individual or combined 0PMs and SA patterns during image recording. The optimum aberration phase to be induced was investigated for different specimens, nonlinear signals and depth locations. Results show that particular combinations of both 0PMs and SA can yield improved images. Moreover, those controlled combinations of phase conditions increase depth-of-focus within the sample independently of the specimen-induced aberrations.

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Spatial Light Modulation Two Photon Microscopy for High Frequency Functional Imaging

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The most popular technique for the acquisition of functional fluorescence signals (e.g. Calcium imaging) in thick biological samples is laser scanning two photon microscopy, due to the high imaging depth achievable, and low photodamage and photobleaching. However, the frame rates achievable in such experimental procedure are severely limited by the serial nature of the acquisition, limiting the acquisition speed to a few frames per second over wide fields of view. In order to overcome this limitation, it is possible to employ a spatial light modulator (SLM) for parallel acquisition over multiple points of interest. Previously reported implementations of SLMs in two photon microscopy required the acquisition of an image through a standard galvanometric scanner [1], followed by the illumination of points of interest through the SLM. This requires complex coordinate transformations between the scanning image and the SLM input space in order to precisely position the points of interest [2]. We present a simpler and fully digital setup capable to collect 3D two photon images by only exploiting the SLM. This configuration leads to an accurate placement of points of interest throughout the field of view, and has the advantage of working without the need of mechanically moving parts. The system was successfully employed for high speed two photon calcium imaging on acute cerebellar slices, achieving frame rates of up to 1 kHz, while monitoring the activity of hundreds of neurons [3,4].

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Optimization-based light-sheet generation**

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The light-sheet microscope is fast becoming a tool in the armory of biologists for the imaging of biological samples [1]. For this technique the axial resolution of the light-sheet microscope [2] is determined by the thickness of the light-sheet used. The current techniques for generating this light-sheet include the use of cylindrical lenses, beam-scanning with galvanometric mirrors and the generation of so-called Bessel beams [3]. For a focused Gaussian beam there is an approximate quadratic relationship between the size of the focal spot and the depth of field. As a result of this relationship, it is unavoidable for a light-sheet microscope that the edge of the field has a worse axial resolution than at the center and one must trade beam uniformity over the field to maximize axial resolution at the center. We present an approach using optimization techniques to engineer a beam that is uniform over the field-of-view whilst retaining the thin axial sectioning of the center. Our method includes the optimization of a set of M odd-polynomial functions to fulfil our designed cost criterion. The light-sheet is then generated from these coefficients by the use of a spatial-light modulator (SLM) or a custom phase plate. We present simulations of this technique, the plan for the experimental realization and the initial results.

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Conjugate Adaptive Optics in Microscopy with Partitioned Aperture Wavefront Sensing

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A common source of aberration in microscopy is nonuniform interfaces between the object and the objective lens. We demonstrate a technique to compensate these aberrations using conjugate adaptive optics (AO), in which the deformable mirror and the wavefront senor are optically conjugate to the interface aberration. We use partitioned aperture wavefront sensing to provide a direct measure of wavefront error in conjugate AO, extending that technique to accommodate non-uniform illumination of the aberration layer by the object. We demonstrate real-time control with an efficient, fast, and robust algorithm using PAW feedback to a MEMS deformable mirror. We demonstrate that in microscopy applications, the conjugate AO approach can lead to substantial improvement in field of view in comparison to pupil AO.

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Tissue Tomographic Phase Image Contrast Improvement with Adaptive Optics

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We describe the use of spatially incoherent illumination to make tridimensional reconstruction of semi-transparent biological samples using a quantitative phase imaging technique [1]. We propose to use spatially incoherent illumination which creates lateral resolution increase and optical sectioning to image thick samples with intracellular resolution [2].
However, when the nominal working distance of the microscope is changed, the image quality is strongly deteriorated mostly by the spherical aberration created because of the observation through a thick sample with a high Numerical Aperture (NA) objective. To compensate for these aberrations, the setup is coupled with adaptive optics system to enhance the contrast above several hundreds of µm imaging depth. It is the possible to keep a constant resolution on the image along the z-axis.

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Comparison of a Multi-actuator Adaptive Lens with deformable mirrors and its application in in-vivo imaging

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We present the comparison of a Multi actuators Adaptive Lens (M-AL), that can correct high order aberrations, with deformable mirrors. The adaptive lens performance are compared with the one of a membrane and bimorph deformable mirrors used together in a wide field microscope setup, using a Shack-Hartmann wavefront sensor for closed loop control.

The M-AL has the potential to increase the diffusion of adaptive optics to many new applications by simplifying the integration of a wavefront corrector inside existing systems.

As examples of the advantages of the use of the M-AL we present its integration in a confocal microscope and in two different in-vivo bio-imaging platforms such as an OCT ophthalmoscope for small animals and a 2-photon microscope.

Wavefront modulators

Invited talk:

Electrically tunable lenses made of electromechanically active polymers

Federico Carpi

Queen Mary University of London, School of Engineering & Materials Science (UK)

F.Carpi, M.Pieroni, C.Lagomarsini and D.De Rossi

Electrical control of optical focalisation is important in several fields, such as consumer electronics, medical diagnostics and optical communications. As an alternative to complex, bulky and expensive state-of-the-art approaches based on shifting constant-focus lenses, we are currently developing electrically tuneable lenses made of a highly-performing class of electromechanically active polymers, known as dielectric elastomers. This original approach allows focusing tuneability to be achieved with compact size, low weight, fast and silent operation, shock tolerance, no overheating, low power consumption, and inexpensive off-the-shelf materials. The presentation will show ongoing progress and future challenges.

Invited talk:

Sound driven optofluidic lenses for high-speed focusing

Marti Duocastella

Italian Institute of Technology (Italy)

The requirement of accurate z-focus control constitutes a time limiting step for applications as important as laser processing or imaging. Several approaches have been developed to circumvent this problem including mechanical sample translation or the use of varifocal lenses for focal plane shifting. However, in all cases the capacity to control focus is fundamentally limited by inertia to speeds well above 1 ms. In this talk, I will present an optofluidic lens that uses acoustic waves to periodically modulate the refractive index of a fluid and achieve focus scanning speeds at microsecond time scales. Such high speed enables one to simultaneously capture multiple focal planes in brightfield and confocal microscopy, or to uniformly process irregular surfaces for high-throughput laser microfabrication.

Small-Aperture Unimorph Deformable Mirror for Laser Applications

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We present results obtained with the further developed version of our miniaturized unimorph deformable mirror. The mirror is dedicated to be used for intra-cavity aberration compensation in high-power solid state lasers. Improved assembly and connection techniques were developed to prevent electrode print-through, providing diffraction limited surface figures. Long term stability, dynamic behaviour, and open loop performance have been significantly enhanced by design modifications of the piezoelectric element.

Materials choice as a new route to Photoconductive deformable mirrors of large dimension

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Photo controlled deformable mirrors (PCDM) are based on an electrostatic membrane where a photoconductive material replaces the conventional electrode pads so that the mirror surface deforms according to a light pattern projected on the photoconductor.
It has been demonstrated that PCDMs allow for a great simplification in the architecture and control system. Indeed the size, distribution and density of the virtual actuators (light pattern) can be easily optimized according to the specific requirements [1,2].
In order to open the route towards specific application of PCDMs (for example astronomy), the increase of the mirror aperture and the improvement of its performances are required.This can be achieved by a suitable design and selection of the photoconductive material.
Therefore we developed theoretical models and we defined the key parameters both geometrical and physical that affect the performances.
We applied this approach to inorganic and organic systems, highlighting the advantages and drawbacks of both technologies, providing general guidelines to the best choice of the photoconductive layer, according to the target application.

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Large aperture photocontrolled deformable mirror based on Zinc

Selenide

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Photo controlled deformable mirrors (PCDM) are based on an electrostatic membrane mirror where a photoconductive material replaces the conventional electrode pads so that the mirror surface deforms according to a light pattern projected on the photoconductor.
It has been demonstrated that PCDMs allow for a great simplification in the architecture and control system [1]. Indeed the size, distribution and density of the virtual actuators (light pattern) can be easily optimized according to the specific requirements [2].
State of the art PCDM apertures are however limited by the crystal size of the photo conductive materials.
We demonstrated the possibility to use zinc selenide, as a photo conductive substrate and we built a 2" PCDM. Both the photoconductive response of the material and the optical properties of the deformable mirror have been fully characterized and compared to theoretical models.
This work opens the way towards large aperture PCDMs thanks to the size scalability of zinc selenide.

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Performance Verification and Environmental Testing of a Unimorph Deformable Mirror for Space Applications

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Concepts for future large space telescopes require an active optics system to mitigate aberrations caused by thermal deformation and gravitational release. Such a system would allow on-site correction of wave-front errors and ease the requirements for thermal and gravitational stability of the optical train. In the course of the ESA project "Development of Adaptive Deformable Mirrors for Space Instruments" we have developed a unimorph deformable mirror designed to correct for low-order aberrations and dedicated to be used in space environment. We briefly report on design and manufacturing of the deformable mirror and present results from performance verifications and environmental testing [1].

[1] P. Rausch, S. Verpoort, and U. Wittrock, "Performance Verification and Environmental Testing of a Unimorph Deformable Mirror for Space Applications," *in Proceedings of the 10th International Conference on Space Optics (ICSO)*, Tenerife, Canary Islands, Spain (2014)

Concept of a large unimorph deformable mirror with a compliant mounting structure

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The efficiency of high power laser facilities suffers from wave front aberrations due to several thermal and mechanical effects [1]. Deformations caused by mounting forces or thermal lensing due to high power density within the laser amplifiers lead to wave front inhomogeneity and high peak power resulting in damage of optical elements [2]. Deformable mirrors (DM) are used to compensate for such aberrations for several years. Depending on the position within the amplifier chain the beam diameter reaches 200 mm or more, which requires active elements of the same size in minimum. One challenge in fabrication large unimorph DMs is to keep high quality optical (flat) surfaces after the two key steps: bonding and mounting and reduce gravitational sag in horizontal, vertical or 45-degree- operating position. This study presents a method for mounting large aperture DMs with a compliant support structure. The concept of the DM is presented and it was shown that mounting with silver filled silicone cylinders (NUSIL CV2-2646) is possible to reach low gravitational sag (9 nm RMS, vertical) and high piezoelectric stroke (>13 µm PtV). It was demonstrated that the mount induces negligible surface deformations using 50-mm-aperture sample mirrors.

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Adaptive Polymer Lens development for applications in the VIS-SWIR-MWIR

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Sandia National Laboratories and the Naval Research Laboratory have been working on the development of large aperture (19.5 mm) adaptive polymer lenses (APLs). This

technology can be used for tactical imaging applications, and more specifically for push-button adaptive optical zoom systems for variable magnification [1].
The bulk of the research was performed for direct view optics in the visible regime [2]. A lot of the effort was place on quantification, identification, minimization and control of optical aberrations due manufacturing processes.
A system was built and demonstrated using these APLs. The lessons learned were expanded to infrared imaging systems [3]. This paper presents an overview of the achieved results for the visible, short- and mid-wave infrared regimes at the component and system level. We also present the current work on the use of these lenses for other applications such as: beam control for variable divergence systems and for pointing or illumination.

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Liquid crystals

Invited talk:

Deep tissue imaging and analysis by optical time-reversal

Changhuei Yang

California Institute of Technology (USA)

We appear opaque because our tissues scatter light very strongly. Interestingly, optical scattering is deterministic and can be time-reversed in much the same way a ricocheting billiard ball can be made to retrace its trajectory if nudged appropriately. I will discuss out recent results in using ultrasound tagging in combination with digital optical phase conjugation to focus light tightly and deeply within biological tissues. I will also report on our experiments using digital optical phase conjugation to tightly focus light on a moving target in a scattering medium. This technology can potentially enable incisionless laser surgery, targeted optogenetic activation, high-resolution biochemical tissue imaging and more.

Hologram recording and reconstruction using Shack–Hartmann sensor and spatial light modulator

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Propagation through atmosphere is a major limitation in free space QKD implementations. Adaptive optics can be a solution to this problem. This paper describes the first results of our investigation using a deformable mirror. Quantum Key Distribution (QKD), first introduced by Bennet and Brassard in 1984 [1], is a method of exchanging cryptographic keys between two users that exploits the laws of quantum mechanics in order to guarantee its security. Since then many experimental setups have been implemented both in fiber and free space [2,3]. The former are already on the market, nevertheless the free space channel is attracting the community since it can guarantee world-wide secure communication through single photon earth satellite links. The major limitation of the free space channel are the perturbations introduced by the atmosphere. In this sense the need for a fast correction of the jitter accumulated during the propagation in the free space channel has been pointed out many times[4,5]. Adaptive optics (AO) can be the optimal solution to this problem allowing a better spatial filtering: a better optical conjugation between the transmitter and the receiver and a consequent rejection of noisy photons coming from other direction. We propose a tilt correction AO system that we integrated in our QKD experimental setup.

Active Light Shaping using GPC

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Generalized Phase Contrast (GPC) is a light efficient method for generating speckle-free contiguous optical distributions using binary-only or analog phase levels. It has been used in applications such as optical trapping and manipulation, active microscopy, structured illumination, optical security, parallel laser marking and labelling and recently in contemporary biophotonics applications such as for adaptive and parallel two-photon optogenetics and neurophotonics. We will present our most recent GPC developments geared towards these applications. First, a compact GPC Light Shaper implementation based on our latest theoretical derivations is used to demonstrate the benefits for typical applications where lasers have to be actively shaped into particular light patterns. We then show the potential of GPC for biomedical and multispectral applications where we experimentally demonstrate the active light shaping of a supercontinuum laser over most of the visible wavelength range.

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A. Bañas, O. Kopylov, M. Villangca, D. Palima, and J. Glückstad, "GPC Light Shaper: static and dynamic experimental demonstrations," Opt. Express (2014).
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J. Glückstad and P. C. Mogensen, "Optimal phase contrast in common-path interferometry.," Appl. Opt. 40, 268–82 (2001).

Improving the performance of LCOS spatial light modulators for adaptive optics applications

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Liquid crystal on silicon (LCOS) technology is well established over last decades first in display technology [1] and now in photonics applications [2]. The specificity of photonics applications (e.g. in adaptive optics) imposes new requirements, challenges and opportunities in further development of the LCOS SLM technology. We transferred the wafer-level based LCOS technology into the field of non-display applications. We will discuss developing of SLMs with larger resolution (1920x1080 and more), dynamic range

(multiple wavelengths), reflectivity (reduction of interpixel gap, implementation of highly reflective dielectric stack), adaptation of the spectral band, flexible driving options (with or without standard video interface).

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AO systems

Active Optics for space applications: developments at ESA

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The increasing need for higher resolution for space optical applications has led to the development of technologies aimed at improving imaging performance beyond what is currently achievable by classical optical systems.
Active Optics is a very promising example of such technologies, tackling in-flight effects (e.g. thermo-elastic deformations, radiation effects on optical materials, desorption…) which impact the optical quality of space instruments. As such, Active Optics can be considered as an enabling technology for future missions using large mirrors. Its use can also potentially decrease the manufacturing complexity of optical components and reduce the outage rate of missions (due e.g. to Sun baffle intrusions or eclipses altering the thermal conditions within the instrument).
This communication gives an overview of the current state-of-the-art of Active Optics developments for Space Applications at the European Space Agency, detailing the constraints that such systems would encounter during a Space mission and listings effects affecting image quality that Active/Adaptive Optics could help reduce.

Developing Adaptive Optics Simulators for the 1.8 meter telescope

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Adaptive Optics (AO) system for a ground telescope consists of four components wavefront sensor, deformable mirror, control system, and reference source. Based on the parameters, such as Fried parameter, outer scale, wind speed, and wavelength, the AO system is required to optimize the components: number of sub-aperture and actuator, actuator stroke, and correcting speed. For the development of an AO system for the Bohyunsan 1.8 meter telescope, simulators have been developed to estimate performance in various parameter changes. Two simulators have been set-up.
Atmosphere simulator provides turbulent wavefront, and AO correction simulator corrects the distorted wavefront caused by the atmosphere simulator. The continuous distorted wavefront is created by Matlab used in numerical AO simulation. In the closed-loop operation, the deformable mirror creates continuously moving turbulent wavefront. It moves in given direction and speed as if the AO system works in the real

site condition. In the AO simulation we will tweak parameters to achieve an optimized performance. For example, we can compare various wavefront sensors and different influence functions. In this paper, we present our on-going characterization of the AO simulators performances.

Optical field reconstruction with digital micromirror interferometry

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The Digital Micromirror Device (DMD) has found many applications in scientific imaging, sensing and wavefront control [1]. A DMD-based wavefront sensor, based on time-multiplexed sampling of the pupil has been reported recently [2]. In this work we investigate the possibility of interferometric optical field sensor with DMD forming a series of sampling interferometers in the pupil of an optical system. If only two micromirrors are turned on, they form a two-point Young's interferometer, with interferometric pattern observed in the focus of the lens. The phase difference between the two reflected beams, with respect to the origin, can be directly obtained from the position of the interferometric pattern, while the intensity in the sample point can be calculated from the brightness of the interference pattern. The field in the whole pupil, with respect to the fixed reference micromirror, can be reconstructed by measuring the values of phase and intensity, micromirror after micromirror, for all micromirrors in the pupil.Our preliminary experiment validates the feasibility of our approach for the field reconstruction in the case of coherent field. We believe that this approach can be extended to sensing of speckle patterns and even incoherent fields, by analyzing not only the intensity and phase, but also the amplitude and the visibility of the interference patterns. Such analysis would yield the complete complex amplitude and/or coherence function, making the approach directly applicable to a wide range of inverse source problems in optics.

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Development of a scalable generic AO kernel for the next generation of ELTs

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The main objective of the present project is to explore the viability of a scalable, generic adaptive optics (AO) control system based exclusively on Field Programmable Gate Arrays (FPGAs), making strong use of their parallel processing capability. A large part of the computational algorithms used for AOcontrol are common irrespective of the telescope that theyare used on. The target is to implement a generic platform which can incorporate popular wavefront sensing and correction techniques through abstraction of the AO geometries as described by Southwell, 1980 [1]. With the advent of extremely large telescopes(30 m -- 100 m), we find the need for incorporating AO asan indispensable part of these telescopes. A scalable Wavefront Processing Unit (WPU) and a modified MVM (matrix vector multiplier) has been implemented on the FPGA as part of the Real Time Controller (RTC). We have made use of a targeted compression algorithm and the AO geometry to make MVM feasible to be implemented on the Xilinx Virtex-7 series of FPGAs.

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Holographic Adaptive Laser Optics System (HALOS)

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We present progress on our holographic adaptive laser optics system (HALOS) - a compact, closed-loop aberration correction system that uses a multiplexed hologram to deconvolve the phase aberrations in an input beam. The wavefront characterization is based on simple, intensity measurements of fixed focal spots and does not require any complex calculations. As such, the system does not require a computer in the loop and is thus much cheaper, less complex and more compact than conventional approaches. Additionally, since the sensing is based on parallel, all-optical processing, the speed is independent of actuator number – running at the same bandwidth for one actuator as for a million.

We present details of a fully functional, closed-loop prototype incorporating a 62-element MEMS mirror, operating at a bandwidth of over 10kHz. The system uses off-the-shelf components and fits entirely on a 0.4x0.6m breadboard.

Lasers

Invited talk:

Adaptive optics for High Power Lasers

Bruno Le Garrec

ELI Beams (Czech Republic)

Using adaptive optics in lasers is only less than 20 years old. Everything started in the 90's when people where dreaming at powerful laser beams propagating over long distances and still being able to damage some flying device. The first laser systems to be equipped with adaptive optics are the fusion lasers: NIF in the US and LMJ in France. This was possible because wavefront sensors were becoming available and because many attempts were made to successfully design and operate large size deformable mirrors. I will give an overview of the different techniques used together with some specific tricks coming from using adaptive optics in laser systems.

Adaptive optics systems deployed on a 100J, 10 Hz cryogenic cooled amplifier system.

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A high average power amplifier system capable of producing 100 J at 10 Hz has been designed and is being constructed [1]. To ensure a good wavefront quality at the output, suitable for experiments, we have incorporated two different AO systems.
The front end delivers a seed of ~300 mJ into the 10 J multipass amplifier which operates at 10 Hz. The first AO system is deployed within this amplifier; consisting of a PHASICS SID4 quadriwave lateral shearing interferometer[2] and a deformable dielectric coated mirror with a 30 mm active region. The deformable mirror uses 49 piezo actuators controlled via a high voltage electronic box. A prototype of this mirror has been installed on the 10 J DiPOLE amplifier, which uses the same amplifier technology, to evaluate the performance of the deformable mirror.
The second AO system is installed on the 100 J amplifier, another multipass amplifier which is seeded with the output from the 10 J amplifier. This AO system employs an Imagine Optics HASO wavefront sensor and an ILAO deformable mirror. The mirror

consists of 52 mechanical actuators and has an active size of 80 mm. The deformable mirror cannot be operated in closed loop in this position, the alternative mode of operation will be described.
Both adaptive optics systems have been evaluated off-line, the results of which will be discussed. Currently both AO systems are being installed on the 100 J laser system and initial measurements of the performance of the system will be reported.

[1] P. Mason et al 2014 "In Design of a 100Joule, 10Hz HEC-DPSSL Power Amplifier ", paper presented at *HEC-DPPSL Conference,* Oxford, UK.
[2] S. Mousset et al 2006, "Piston measurement by quadriwave lateral shearing interferometry", *Optics Letters* Vol. 31, No 17, pp 2634-2636

Adaptive Optics loop implementation and optimization for petawatt laser facilities

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We present new advanced features allowing to optimize completely the high power laser installations. The aim is to have a complete control of the focal spot in terms of quality and location. These two conditions are necessary to optimize the energy deposited on the target during laser matter interaction experiments.
We will present how it is possible to optimize completely the focal spot quality by correcting the aberrations of a whole laser installation including the aberrations introduced by the last focusing optics. For this, an Adaptive Optics (AO) loop is made at low power directly on the diverging beam with the wave front sensor located in the chamber after the focal spot. This AO loop configuration leads to a diffraction limited spot. This method is based on the ability of 4 Wave Lateral Shearing Interferometer to measure high numerical aperture beam up to f/1.5.
We will present how it is possible to concentrate the light power at a very precise location. For this, the AO loop can be used to change in real time the focus position in the chamber along the 3 dimensions by modifying the combination of tilt and defocus added on the phase map used as order for the loop.

Adaptive optics system for HiLASE high average-power multi-slab laser system

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Within the framework of the Hilase project a high average-power diode pumped cryogenically cooled multi-slab laser system is being developed at the Central Laser Facility, Rutherford-Appleton Laboratory, Harwell, England in collaboration with Hilase team. The system will deliver pulses of energy up to 100 J at a repetition rate of 10 Hz. The high average-power nature of the system results in high thermal loading being induced in the gain media and motivates the need for efficient wavefront correction in order to maintain high beam quality.
The system incorporates two multi-pass amplifiers first of which amplifies the pulses to 10 J energy and second up to 100 J. The 10 J multi-slab amplifier head was modelled both numerically and experimentally. Based on these simulations, a set of working conditions for the adaptive optics system has been put together so that the wavefront correction would be sufficient for obtaining a diffraction limited beam. The closed loop uses data from SID4 quadriwave lateral shearing interferometer as correcting loop feedback signal. So far, three deformable mirrors have been developed in the framework of this study and all these mirrors have been characterized and their performance tested. Results of the characterization and performed tests clearly indicate perfect suitability of this adaptive optics technology for wavefront correction in the Hilase multi-slab laser system.

Beam shaping of femtosecond pulses with diffractive optical elements: spatio-spectral and temporal dynamics

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Ultrafast femtosecond lasers have found many applications in fields like spectroscopy, high-field physics, medicine or laser processing. Some of these applications have been demonstrated to benefit from diffractive shaped beams [1]. A common approach to obtain a shaped profile is by means of a phase-only diffractive optical element (DOE) and a Fourier lens. However, due to the broadband nature of femtosecond pulses, space-time coupling effects can happen since the shaped profile is formed for a given wavelength [2]. A complete characterization is thus mandatory to assess the usefulness of diffractive shaped pulses for further applications. In this contribution, we report the complete spatiotemporal dynamics and propagation of femtosecond shaped pulses by using the STARFISH technique [3]. The experimental results are corroborated by computer simulations based on the solution of the Fresnel equation. In particular, we have analyzed a Gaussian-to-flat-top DOE and a diffractive lens. Space-time coupling effects are observed in both cases. The ring structure of diffractive lenses gives rise to a train of pulses in the temporal domain [4]. In contrast, femtosecond FTBs presents a monotonically increasing beam size with the wavelength and a curvature in the pulse front. The results of this study will be helpful, for example, to understand the filamentation dynamics with DLs [5] and to assess the validity of top-hat shapers for femtosecond laser processing.

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Adaptive Optics for ultrashort pulse manipulation

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The manipulation of the temporal profile of ultrashort laser pulses is one of the basic tools for coherent control of a large number of photoinduced mechanisms, from chemical reactions to biological processes. Shaping of femtosecond light pulses is typically performed in the frequency domain, by manipulation of the pulse spectral intensity and, more important, of its spectral phase. One of the tools proposed for phase control uses the 4-f stretcher: the frequency components of a pulse are dispersed by a prism or a grating, collimated, and sent back by a folding mirror. By using a deformable mirror in place of the flat folding optics, one can finely control the optical path of each component, and hence manipulate its spectral phase. This technique is able to compress femtosecond pulses down to their transform-limited duration, demonstrating the great potential of Adaptive Optics for ultrafast lasers [1]. Obtaining the mirror shape for pulse compression requires two steps [2]: measure the pulse spectral phase and introduce the phase which compensates for its distortions. Such process is iteratively repeated till a fine phase correction is obtained. In this work we show that, by including a suitable mirror and characterization technique in a closed loop, we could get this procedure to automatically correct spectral phase distortions accumulated in an optical chain. The mirror is deformed by piezoelectric actuators, while the spectral phase is detected by the SEA-TADPOLE technique [3]. In few automatic iterations, the closed loop is able to calibrate the mirror and correct for the spectral phase distortions introduced by glass plates of various thicknesses on the optical path.

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Wide aperture adaptive optics for high power CO2 laser beam control

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This paper presents the results of high power CO2 laser aberration correction and jitter stabilization. A bimorph deformable mirror and two tip-tilt piezo correctors were used as executive elements. Two types of wavefront sensors – Hartmann to measure higher order aberrations (defocus, astigmatism etc.) based on infrared uncooled microbolometer camera produced by INO, Canada, and another – tip-tilt one based on Russian technology of thin film deposition on Si substrates, were applied to measure wavefront aberrations. We discuss both positive and negative attributes of suggested wavefront sensors. The adaptive system allowed to reduce aberrations of income laser radiation by 7 times (P-V) and to stabilize jitter of incoming beam up to 25 µrad at a speed of 100 Hz. The adaptive system frequency range for high order aberration correction was 50 Hz.

Doughnut-like and super-gaussian beam formation in closed-loop with Shack-Hartmann wavefront sensor

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It is desired to use some special intensity distribution on the target for various industrial applications. The adjusting of the intensity profile can be implemented by means of adaptive optics. In this paper we present laser beam control in the focal plane of lens with bimorph deformable mirrors. Hill-climbing method and stochastic algorithm are compared. Advantages and disadvantages of two methods are discussed.