Correction of Atmospheric Effects on Laser Beams Propagating through Strong Turbulence

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***Abstract*— Atmospheric effects limit the performance of any electro-optical (EO) system. Tasks such as delivery of directed energy and laser communications are significantly affected by turbulence and refraction. A correction of atmospheric effects on the propagation of light can be done by adaptive optics (AO). Nevertheless, challenging scenarios like strong turbulence near the ground lead to high failure rates of the traditional AO systems. Unconventional wavefront sensors and sensing strategies are developed at Fraunhofer IOSB to provide alternatives for measuring the wavefront deformation of a laser beam and to improve the performance of energy delivery and laser communications applications even in strong turbulence and/or horizontal- or slant-path propagation.**

Keywords*— Lasers and electrooptics, lasers, adaptive optics

I. INTRODUCTION

Adaptive optics (AO), a technology which encompasses a variety of electro-optical systems aiming at measurement and correction of optical deformations in real time, has found many applications in today's World: astronomy, in vivo imaging of human retina, vision correction, laser machining, remote sensing, tracking and high-resolution imaging of satellites, missile defence, communications and even entertainment (in DVD players), to name just a few. The systems and methods of AO are crossing over to consumer market because of constant decline in prices of deformable mirrors and speed-up of computations available on a personal computer.

II. STATE OF THE ART

The well-established Shack-Hartmann wavefront sensor (SHS) is a workhorse solution in astronomical AO. However, two fundamental characteristics handicap the application of this sensor to more challenging scenarios like laser propagation over long horizontal paths within extended-volume turbulence, which produce scintillation and branch points in the wavefronts. Firstly, due to the procedure of wavefront reconstruction, the bandwidth of SHS is limited. This has consequences for deploying SHS-based AO systems on moving platforms and/or for satellite tracking. Secondly, SHS is highly sensitive to scintillation effects. Obscurations or saturations of parts of the sensor's pupil can lead to significant failure rate of the wavefront reconstruction process.

The weaknesses of the SHS seem to be the strengths of the so-called holographic wavefront sensor (HWFS). In this sensor there is no need for time-consuming matrix-vector multiplications inherent to SHS-based AO systems. Besides the potentially exceptional bandwidth capabilities of HWFS, the operational principle of the sensor is insensitive to partial pupil obscurations. These characteristic features make HWFS an ideal candidate for sensing atmospheric effects on laser propagation.

In scenarios where wavefront measurement is either extremely challenging or ambiguous, which occur quite often in strong turbulence, the concept of "wavefront-sensorless" AO has become established. Here use is made of iterative algorithms which "guess" various combinations of optical deformations until an improvement in image or laser beam quality is observed. Naturally, when applied to strong atmospheric turbulence the methods must be exceptionally fast in their convergence rate. The most famous method, the stochastic parallel gradient descent (SPGD), is inherently "blind", i.e. it does not make any assumptions about the nature of the aberrations.

In order to improve the convergence rate of SPGD the modal version of the algorithm, M-SPGD, was proposed. In SPGD, one perturbs randomly the actuators on the deformable mirror and the beam quality metric is checked for improvement. This can become a highly-dimensional problem for modern deformable mirrors with many actuators. To reduce the number of degrees of freedom one can project the actuator space onto an orthogonal modal basis, e.g. Zernike polynomials and perturb these instead of actuators. Additional advantage of this approach is that one can include known turbulence statistics into the algorithm e.g. by optimizing gain of the algorithm for each mode.

III. SUMMARY

Two alternative approaches to SHS-based wavefront sensing have been proposed: the holographic wavefront sensor and modal SPGD. They address three shortcomings of the conventional method: sensitivity to scintillation, bandwidth limitation and the ambiguity of wavefront estimation. As such they provide promising alternatives for applications involving light propagating through strong atmospheric turbulence.

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