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Automated single-mode fiber coupling at the focal plane of an optical ground station

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Abstract

The increasing need for secure, high-data-rate communications has motivated research in the field of free-space optical (FSO) communication technologies. FSO links offer significant advantages over conventional radio-frequency (RF) systems, including higher available bandwidth and inherently improved confidentiality due to their narrow beam divergence. In addition, the further development toward satellite-based FSO telecommunications provides an attractive framework for achieving fundamentally secure long-distance communications using Quantum Key Distribution (QKD). Nevertheless, several obstacles, such as atmospheric turbulence and imperfect mechanical alignment, severely impact the performance of these communication methods, as they degrade the single-mode fiber (SMF) coupling efficiency at the optical ground station.

This research focuses on the correction of the non-common path aberrations (NCPA) caused mainly by imperfect mechanical alignment in a fiber-coupled optical system. These aberrations appear downstream of the wavefront sensor (WFS) and must be corrected through measurements at the focal plane, located at the optical fiber entry. The measurements, performed using a power meter, guide a wavefront sensorless adaptive optics (WSAO) system, which includes a fast-steering mirror (FSM) and a deformable mirror (DM). The division of tasks between the FSM and the DM is necessary to avoid exceeding the stroke limit of the DM, but constitutes a major challenge for the design of the correction procedure. Moreover, the maximum power that can be coupled into the optical fiber is not known, which also complicates the calibration of the system.

To address the different challenges, this work first proposes a review of the theoretical principles of optical fibers and optical aberrations. An in-depth investigation of SMF coupling is then conducted and applied to the studied optical system. This is followed by a sensitivity analysis of the fiber coupling efficiency (FCE) with respect to variations in the considered optical system. Based on this study, an automated calibration procedure is proposed and implemented through the Multi-Stage M-SPGD (MSM-SPGD) algorithm, a novel adaptation of the Modal-Stochastic Parallel Gradient Descent (M-SPGD) introduced in this work. The design of this calibration algorithm is validated through simulations under various perturbation scenarios. Within its operational limits, the algorithm systematically converges to the nominal state of the system, recovering near-maximum FCE. Experimental results further confirm its effectiveness, showing that the algorithm significantly increases the power coupled into both multimode fibers (MMF) and SMF, and effectively compensates system aberrations. These results demonstrate that the MSM-SPGD algorithm provides a reliable and practical solution for maximizing fiber coupling in adaptive optical systems.