Laboratory validation of a laser shaping system before guide star projection

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ABSTRACT

Multiple sodium laser beacons are a crucial development in multi-conjugate adaptive optics systems that offers wide-field diffraction limited adaptive optics correction to the astronomical community. This correction is strongly dependent on the laser beam power and quality, so a beam shaping concept is currently being developed to speed-up calibration and alignment of the laser before every run. A method previously reported, has now been implemented on a laboratory bench using MEMS deformable mirrors. Necessary calibration and characterization of the deformable mirrors are described and the results for experimental amplitude correction are presented.

Keywords: laser beam shaping, phase retrieval, optical field conjugation, deformable mirrors

1. INTRODUCTION

Adaptive optics (AO) systems compensate for image distortions induced by the Earth’s atmosphere. Many AO systems use laser guide stars (LGS) in order to probe and correct for atmospheric turbulence over a larger portion of the sky. In this way, LGSs have a large impact on astrophysical and science capabilities in current ground-based telescopes, such as Gemini South and Keck. Furthermore, LGS systems will be a must in the next generation of large telescopes, such as the TMT and GMT.\textsuperscript{1,2}

In order to probe the atmospheric turbulence, wavefront sensors (WFS) are required. For Shack-Hartmann wavefront sensors the measurement error is strongly dependent on the spot size and the number of photons received from the guide stars. The greater the number of photons is received in the sub-aperture, the more accurate the measurement.\textsuperscript{3,4} For this reason, high quality and powerful lasers are needed.

Despite the significant advances in LGS technologies, the complex and time consuming alignment procedures of the laser source reduce the availability of instruments such as the Gemini South LGS AO system.\textsuperscript{5} The concept of a beam shaping system for Gemini South LGS AO was recently proposed.\textsuperscript{6} Preliminary simulations of the uplink propagation of the laser toward the sodium layer has been studied to improve GeMs laser efficiency.\textsuperscript{7}

In order to optimize the laser beam to be launched, correction of both amplitude and phase distortions of the beam is required with the least possible loss of energy. Hence, only refractive or reflective surfaces should be used to redistribute the energy. Deformable mirrors (DM) are chosen for this concept. In this project, we aim to experimentally verify the algorithm previously reported.\textsuperscript{8} In Sect. 2, the architecture of the laser beam shaping with 2-DM is described. Also the iterative algorithm to solve the problem is explained. In Sect. 3, laboratory setup and preliminary DM characterization are detailed. In Sect. 4, the experimental results are presented.

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2. 2-DM ALGORITHM FOR AMPLITUDE AND PHASE CORRECTION

In order to correct both amplitude and phase distortions of the laser beam, the architecture with 2-DM described in Fig. 1 has been proposed. It is out of the scope of this paper to detail and study the algorithm used to control the 2 DMs but the principle is briefly described below. For more details on the algorithm, the reader is referred to Guesalaga et al.\textsuperscript{6} and Béchet et al.\textsuperscript{8}

The laser beam incident on DM1 is given by the field \( U_L(x) \), such that

\[
U_L(x) = u_L(x) \exp(j \varphi_L(x)), \tag{1}
\]

where \( x \) is a vector of coordinates in a plane perpendicular to the direction of propagation, \( \varphi_L(x) \) and \( u_L(x) \) are given by the aberrated phase and amplitude respectively in a plane conjugated to DM1. \( U_1(x) \) is the field leaving DM1,

\[
U_1(x) = U_L(x)m_1(x)\exp(j \varphi_1(x)), \tag{2}
\]

where \( \varphi_1(x) \) is the phase pattern applied to DM1 and \( m_1 \) represents the reflection mask of the mirror. The incident field \( U_z(x') \) on DM2 is given by the propagation of \( U_1(x) \) from the plane of DM1 to DM2. The near-field propagation at distance \( z \) between DM1 and DM2 is modeled with the Fresnel propagation integral and computed using angular spectral propagation techniques.\textsuperscript{9, 10} The output field is

\[
U_2(x') = U_z(x')m_2(x')\exp(j \varphi_2(x')), \tag{3}
\]

where \( \varphi_2(x') \) is DM2 phase correction and \( m_2 \) represents the mask of this mirror pupil. DM2 is conjugated to the projecting aperture such that \( U_2(x') \) is assumed to be the transmitted field. Finally, the desired output field is

\[
U_t(x') = u_t(x')\exp(j \varphi_t(x')), \tag{4}
\]

where \( u_t(x') \) is its amplitude and \( \varphi_t(x') \) its phase.

Assuming \( U_L \) and \( U_t \) known, the goal of the algorithm is to find the right values for \( \varphi_1 \) and \( \varphi_2 \) to be applied to DM1 and DM2 to generate the desired field \( U_t \) on the projecting aperture.\textsuperscript{11} For this purpose an iterative phase retrieval method is used to estimate the phase shapes \( \varphi_1 \) and \( \varphi_2 \) that match the amplitude and phase constrains in DM1 and DM2 planes, connected by a propagation relation (see Fig. 2). The algorithm to be used
in this project is a version of Gerchberg-Saxton method\textsuperscript{12} adapted to account for the near-field separation of the DMs with a novel and regularized unwrapper method to obtain phase functions $\varphi_1$ and $\varphi_2$ likely to be efficiently reproduced by the continuous sheet of a DM.\textsuperscript{8}

In this algorithm, the deformation applied on DM1 redistributes the amplitude at the output plane (after DM2). In the remainder of this paper, a laboratory setup is presented to validate this amplitude shaping with a single DM (DM1). The second DM will be added in a further work.

![Block diagram of the phase-retrieval technique used in order to control the amplitude and the phase of the field at distance $z$ from the DM.](image)

**3. EXPERIMENTAL SETUP**

**3.1 Setup description**

This section describes the experimental setup aimed to demonstrate the effectiveness of the amplitude and phase shaping method described above. This setup is shown in Fig. 3.

It is composed of a light source, a Shack-Hartmann WFS (Fig. 3a label E), a MEMS deformable mirror (Fig. 3a label C) and an imaging camera (Fig. 3b) among other optical and optomechanical components (Fig. 3a label A, B, D). The Shack-Hartmann WFS is a Thorlabs WFS150C composed of a 39 × 31 micro lens array with a lenslet diameter of 150 um, that provides high-speed wavefront and irradiance distribution measurements. The light source is a laser diode working at $\lambda = 635$ nm. The Boston Micromachines Inc. MEMS DM is a continuous mirror membrane that is deformed by 140 electrostatic actuators. The mirror has a square shaped membrane of 4.4 mm clear aperture and the 400 um size actuators are arranged in a 12 × 12 array with four inactive actuators at the corners. The camera is a Edmund Optics CMOS camera with 752 × 480 pixels and a pixel size of 6 um (see Fig. 3b).

The experimental setup keeps the DM surface in a plane conjugated with the Shack-Hartmann lenslet array. This optical conjugation is important because it allows to measure the deformations of the DM surface with the WFS.
Figure 3: Images of the experimental set-up (a) A, B: Collimation optics. C: Deformable mirror. D: Relay optics. E: Shack-Hartmann WFS. F: Flat mirror redirecting the beam toward the imaging CMOS Camera (b) used to perform the laboratory validation of the method for laser amplitude shaping with the DM1.

The control computer is a general purpose PC with Intel Core 2 Duo processor, running the algorithm under Windows 7. The amplitude of the laser source, $u_L$ in Eq. (1), is measured using the software provided by Thorlabs. Given the setup configuration, a flat incident phase $\varphi_L$ in Eq. (1) is assumed. These amplitude and phase, $u_L$ and $\varphi_L$ are inputs to the algorithm. The control computer also generates the actuator values produced by the algorithm and reconstruct the DM surface from the WFS measurements. Previously, the DM's software must be setup with the coefficients of the quadratic voltage-deflection curve that models the behaviour of the actuators (the characterization of this curve will be detailed in Sec. 3.2.1). Finally the resulting image at distance $z$ (distance between DMs assumed in the algorithm) is recorded by the CMOS camera placed on a tripod and located after the mirror F (Fig. 3a). In Section 4, we compare the recorded image against the resulting amplitude estimated by the algorithm.

3.2 DM characterization and calibration

The MEMS DMs are currently a widely accepted technology in wavefront shaping applications given their versatility and precise wavefront control with high spatial resolution. However, electrostatic membrane actuators are susceptible to damage in case of overvoltage. In our experimental setup, the MEMS DM has two damaged actuators whose locations are shown in Fig. 4.

Actuator deflection responds non-linearly to the applied voltage. The actuator response is characterized by the deflection curve coefficients which are unique to each DM. These deflection curves are estimated in Sec. 3.2.1. The damaged actuators of the DM available, also have a characteristic deflection curve. The strategy to find an operational zone for these actuators taking into account different deflection curves are described in Section 3.2.2.
3.2.1 Deflection curves

The surface of the DM membrane is determined by the displacement of each actuator. The knowledge of the voltage-displacement curve is needed to apply arbitrary shapes. Given that the WFS lenslet array is optically conjugated with the plane where the DM is placed, we can measure the deformation of the DM surface using WFS data. In order to get an unique displacement curve, a sequence of separate voltages (from 0 V to 150 V) were applied to different located functional actuators in the 12 x 12 array, keeping all other actuators at zero voltage and measuring the resulting deflection. A set of 64 voltage-deflection data from eight actuators was measured (stars in Fig. 5).

![Figure 5: Voltage-deflection measurements and quadratic fits in the range from 0 V to 150 V. Stars and solid line correspond to 8 different fully functional actuators. Circles, triangles, dashed and dotted-dashed lines correspond to the two damaged actuators shown in Fig. 4.](image-url)
To obtain the coefficients of the quadratic fit, an initial approach to the fit is performed. From the residual errors of the first fit, the mean value and the standard deviation are computed. If there is any point away from the mean value by more than three times the standard deviation (in a Gaussian probability distribution of error, 99.7% are contained in the mean ±3σ) it could be considered to be an erroneous data and be ignored. In our case, just two measurements were considered outliers. Finally, a global quadratic fit is made (solid line in Fig. 5), \( Ax^2 + Bx + C \). The coefficients \( A \), \( B \) and \( C \) are entered as calibration parameters in the DM’s software to send the right voltages for the desired displacements.

### 3.2.2 Deflection curve for damaged actuators

In the same way, a quadratic fit for each damaged actuator was performed (dashed and dotted-dashed line in Fig. 5). The DM control software does not allow to use more than one deflection curve, so the goal of this section is to take into account the particular behavior of the 2 damaged actuators and manage to control them.

As shown in Fig. 5, an operational zone between 0 to 715 nm can be seen where all actuators achieve the desired displacement. For instance, the quadratic fit for damaged actuators is inverted to obtain the voltage \( B \) (see Fig. 6) from the desired displacement \( A \) (Fig. 6). Evaluating this voltage in the global deflection curve (fully functional actuators) allow us to obtain the modified displacement \( C \) (Fig. 6) for each damaged actuator that is finally entered as an input at the DM control software.

![Figure 6: Example of displacement for the damaged actuator represented by the dotted-dashed line. A: Desired displacement; B: Voltage to be applied and C: Modified displacement to send to the DM control software.](http://proceedings.spiedigitallibrary.org/)

### 3.2.3 Characterization of the influence function

The influence function is a characteristic displacement map of the DM surface when a single actuator is poked. This influence function is necessary to accurately control the real shape of the DM taking into account the actuator coupling. A Gaussian influence function is usually employed.\(^{14,15}\) To get the DM’s influence function a sequence of different voltages were applied to several functional actuators and a 1D Gaussian fit in two orthogonal axes is applied on every measured DM deformation. Therefore, we assumed that each actuator (including the damaged ones) have the same influence function well described by a 2D Gaussian function and that the influences add linearly.

The mean full width at half maximum (FWHM) of the gaussian fits of the measured influence functions in the range from 50 V to 150 V is 684 ± 57 um. This is compatible with the values of 20 – 40% inter-actuator coupling given by the manufacturer manual (Fig. 7).
4. RESULTS

In this section we define three different desired amplitude patterns in order to test the amplitude shaping algorithm.

1. A 4\textsuperscript{th} order super Gaussian with a FWHM of about 3 mm at distance $z = 0.5$ m.
2. A ring of 1 mm of radius with Gaussian profile at distance $z = 0.5$ m.
3. Two dots separated 1.8 mm with Gaussian profile at distance $z = 1.5$ m.

Using the experimental setup described in Sec. 3.1, the incident laser amplitude in the DM1 plane is measured (see Fig. 8a). This amplitude is used as an input in the algorithm along with a flat input phase. As an example, the amplitude of the field in the plane placed at $z = 0.5$ m from the DM when it is flat (damage actuators compensated) is registered. This image is shown in Fig. 8b. Note that the amplitude in the image is modulated due to the periodic grid present on the DM surface.

Figure 8: Amplitude maps of the laser beam in two different planes: (a) Amplitude of the input field at DM1 obtained with the optically conjugated WFS and (b) Amplitude of the output field at $z = 0.5$ m from the DM1 when the DM1 is flat (damaged actuators compensated) registered with the CMOS Camera.
The experimental results show images qualitatively consistent, specially in term of size, distance and orientation. The orientation is checked in the two dots results (showed in the third row of Fig. 9). The algorithm also predicts somehow the little disturbance between the dots. It is important to highlight that all images were taken at exactly the distance $z$ as defined in the algorithm.

We suppose that the observed discrepancies between the registered images and the algorithm results are induce by the grid present on the DM surface. Another source of error can still come from the DM characterization, specially in the model of the influence function. That could be improved using other influence function approach. It is worth to mention that the amplitude given by the algorithm (showed in the central column of Fig. 9) do not consider the effects of the influence function in the shape of the DM surface). Last improvement should require characterize and include in the simulations the incident phase at the DM.

Figure 9: Amplitude maps of the output field at DM2 plane: The left column shows the desired amplitude, the algorithm predicted amplitude is represented at the center column and on the right column the amplitude derived from the images acquired with the camera at the same plane. Top row: Test 1 (Super-Gaussian); middle row: Test 2 (Ring) and bottom row: Test 3: (2 dots).
5. CONCLUSIONS
First laboratory validation of the method reported in Guesalaga et al. and Béchet et al. has been successfully performed. It demonstrates qualitatively that the algorithm predict the resulting amplitude at the optical plane of the second DM. Thanks to the calibration of the DM, the amplitude is redistributed to achieve the desired one. To control the deformable mirror in open-loop the characterization process of its deflection curves and coupling is very important. In our case a common influence function was assumed including the damaged actuators. New DM calibration is studied in order to improve the experimental results. Finally, a second mirror will be incorporated in future work, so that the architecture with two deformable mirrors will be fully described and tested in the laboratory.

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