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Letter

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Holographic wavefront sensor for fast defocus measurement

Abstract: Atmospheric effects significantly influence the propagation of light. Conventional adaptive optics systems, based on Shack-Hartmann sensors (SHS), work well for vertical-path propagation. However, for more challenging scenarios like horizontal-path imaging or free-space laser communications through extended-volume turbulence and strong scintillation, the bandwidth of SHS is insufficient. A promising alternative is the holographic wavefront sensor (HWFS). Our paper deals with some dependencies and limitations of the HWFS. First, we show that the sensitivity of the HWFS is highly dependent on the detector size. The smaller the detector, the more sensitive is the sensor. This has consequences in the photon-starved regime, which would naturally occur when the sensor is operated at the intended MHz speed. Second, we show that uncorrected (or residual) tip/tilt has a large impact on the accuracy of the measurement. We present experimental results of measuring an important and also easily correctable aberration, defocus, with the HWFS.

Keywords: adaptive optics; holographic wavefront sensor; holography.

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1 Introduction

Electro-optical systems, whether used for astronomical observations, remote-sensing and surveillance from space, tracking and high-resolution imaging of satellites, delivery of directed energy to space-based platforms, or horizontal-path imaging and laser communications, are always affected by atmospheric turbulence. In the majority of cases, this turbulence imposes a fundamental limitation to their performance. Adaptive optics (AO) systems, consisting normally of a wavefront sensor and a deformable mirror, provide a real-time solution to the problem. In this paper, we focus on the wavefront-sensing part of an AO system.

The well-established Shack-Hartmann wavefront sensor (SHS) is a workhorse solution in astronomical AO [1]. 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. First, 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. Second, 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 [2].

The weaknesses of the SHS seem to be the strengths of the so-called holographic wavefront sensor (HWFS) [3–5]. This sensor type consists of two main components: a holographic diffractive optical element (DOE) and a small detector array. By illuminating the DOE with the beam of interest, it generates for each wavefront aberration (e.g., for each Zernike mode) two spots at predefined locations on the detector array (Figure 1). The amplitude of each aberration can be determined from the normalized intensity difference of both spots. Hence, the modal decomposition of the wavefront into its components is a diffraction process and is carried out at the speed of light. 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. We have tested obscurations up to 33% of the aperture size [6, 7]. Naturally, a decreasing signal would affect the accuracy of the

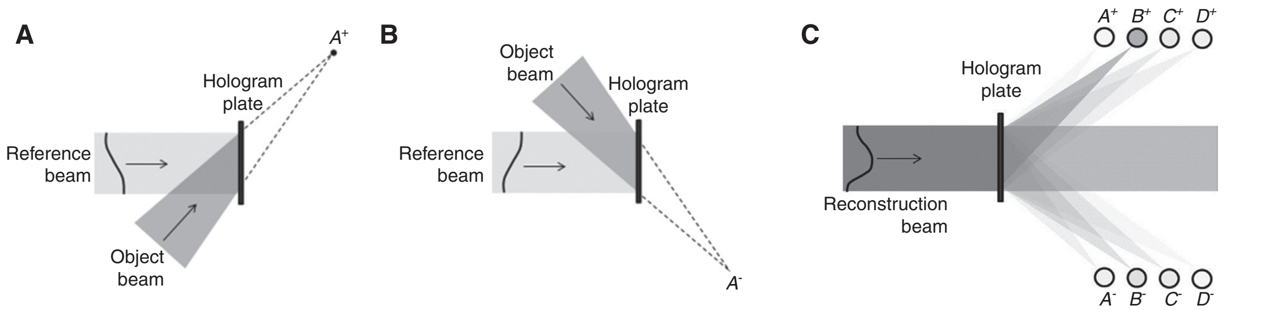

Figure 1 (A) Recording of a hologram with the positive amplitude *+a* of one chosen Zernike mode. (B) Recording with the negative amplitude *-a* of the same mode. The multiplex of both recordings is the core of HWFS for the measurement of one aberration type. (C) The hologram is encoded for the simultaneous measurement of four different Zernike modes (A, B, C, and D). If it is illuminated with a reconstruction beam, light is diffracted in all spots. The intensity difference of the matching spots gives information about the amplitude of a particular Zernike mode. In this example, only the mode B is present in the wavefront.

measurement in the presence of significant noise. These characteristic features make HWFS an ideal candidate for sensing atmospheric effects on laser propagation. Especially, operation under scintillation effects is a very interesting avenue to be explored.

In this paper, our implementation of HWFS for defocus measurement is described together with several dependencies of HWFS we have discovered. We show that the choice of the region of interest on the detector array has a significant influence on the sensor response. Furthermore, we investigate the influence of residual tip and tilt on the performance of HWFS. The measurement of tip and tilt is not intended in the basic HWFS design. In fact, our experiments show that the sensor cannot be used in the presence of beam wander. We concentrate on defocus measurement only because simple theoretical dimensioning [8] suggests that compensating for tip/tilt – with a separate device – and defocus – with HWFS – should result in the value of the Strehl ratio above 10% (reported threshold of usefulness of AO correction for laser communications [9]).

2 The principle of holographic wavefront sensing

The core of the HWFS is a holographic grating, which acts as a diffractive optical element. The holographic principle enables the storage and reconstruction of the full three-dimensional information pertaining to an object [10]. For that purpose, a reference beam is superimposed in the plane of the hologram plate with light coming from the object. After the chemical postprocessing of the plate, the fringes are stored as phase grating. By illuminating this grating with a reconstruction beam corresponding to the reference beam, the light is diffracted into the real image of the object. This reconstruction is highly dependent on the wavefront of the reconstruction beam. If the reconstruction wave does not match the phase-conjugated reference beam, the real image is generated with aberrations. The functioning principle of the holographic wavefront sensor is based on this effect.

Figure 1A and B show the implementation of HWFS for one wavefront aberration: with one hologram plate, two holograms are recorded one after another. The object beams are symmetrically arranged converging beams – they form the foci behind the hologram plate at the positions denoted A^+ and A^-. The reference beams are collimated beams, which have anticonjugated wavefronts corresponding to specific anticonjugated Zernike modes. For the first hologram, the amplitude of the chosen aberration is $+a$, where a is the maximum amplitude of the chosen mode that the HWFS will be able to measure. For the second hologram, the amplitude is $-a$.

After the exposure and chemical processing of the hologram, it can be used as DOE for the laser beam of interest. The incoming light is diffracted into positions A^+ and A^-. It has been calculated that the normalized difference of intensities $(I_{A+}-I_{A-})/(I_{A+}+I_{A-})$, integrated over a small area on the detector, is proportional, within a certain range, to the amount of the measured aberration mode contained in the input wavefront [11]. Any region of the hologram contains a part of the diffraction pattern and, thus, the full information. Consequently, fractional shadowing of the sensor would reduce the *absolute intensities* of the reconstructed spots but would have no influence on the *normalized intensity difference* of the two foci corresponding to one wavefront mode [6, 7].

The goal of our research is to check whether these predictions hold in strong turbulence and whether the sensor is suitable for closed-loop operation. While the theory has been developed for point detectors and stationary

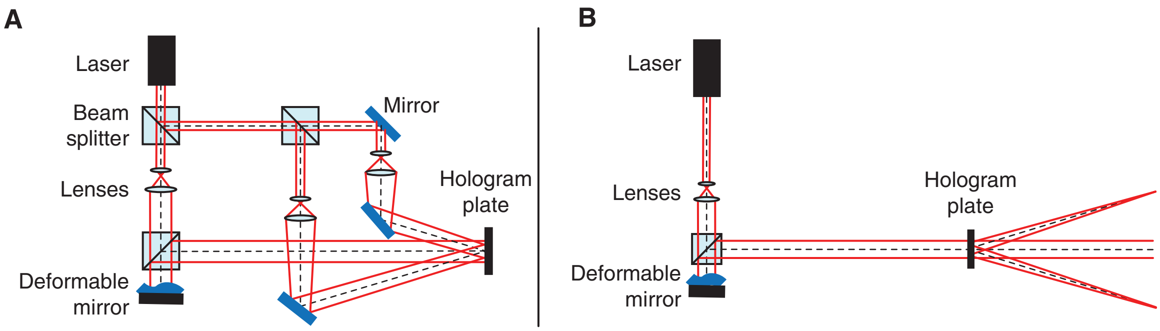

Figure 2 (A) Optical setup of the hologram recording. The laser beam is divided into reference beam (transmitted) and object beam (reflected) by the first beam splitter. The reference beam is directed to the hologram plate after reflecting off the deformable mirror. The object beam is split into two convergent beams. For the first recording of the multiplex hologram, the part of the object beam transmitted by the second beam splitter is blocked, and the reference beam is deformed with a -2λ defocus of amplitude. For the second exposure, the reflected part of the object beam is blocked, and the reference beam is deformed with a +2λ defocus of amplitude. When illuminating the chemically processed multiplex hologram, the two object beams are reconstructed (B).

focal points (assumption of perfect tip/tilt correction), our investigations show significant dependence of HWFS on the detector size.

3 Characteristics of the holographic wavefront sensor

We implemented HWFS for defocus measurement. The hologram recording was realized with a HeNe laser (633-15 P, Qioptiq Photonics GmbH & Co. KG, Goettingen, Germany) (632.8 nm) and a red-sensitive hologram plate (PFG-01, VM-TIM Optomechanische Werke, Jena, Germany) from VM-TIM. Defocus was generated with the deformable mirror (DM-52-15, ALPAO SAS, Montbonnot St. Martin, France) from ALPAO and the recorded maximal and minimal defocus amplitudes were set to +2λ and –2λ, respectively. The optical recording and reconstruction setup is illustrated schematically in Figure 2.

For the tests described here, we aimed at analyzing the spots' characteristics, so we used two charge-coupled device (CCD) detectors (DMK 21BU04.H, The Imaging Source Europe GmbH, Bremen, Germany) with a pixel size of 5.6 µm. In the future, fast photodiodes will be employed.

To determine the response curve of the recorded hologram, the defocus amplitude of the reconstruction beam was varied between -4λ and +4λ. The corresponding spot intensities were detected with the two CCD at the positions A^- and A^+. The measured characteristics are shown in Figure 3A. Simple intensity difference is plotted in Figure 3B. This curve, however, depends on the total intensity of the incoming light. In contrast, the normalized difference provides a more linear and total intensity-independent response [7] (Figure 3C).

To investigate the optimal detector size for the spot detection, the integration area of the CCD was varied. In Figure 4A, the corresponding characteristic curves are compared. The spot size of the reconstructed laser foci for optimal reconstruction (defocus amplitude of -2λ or +2λ,

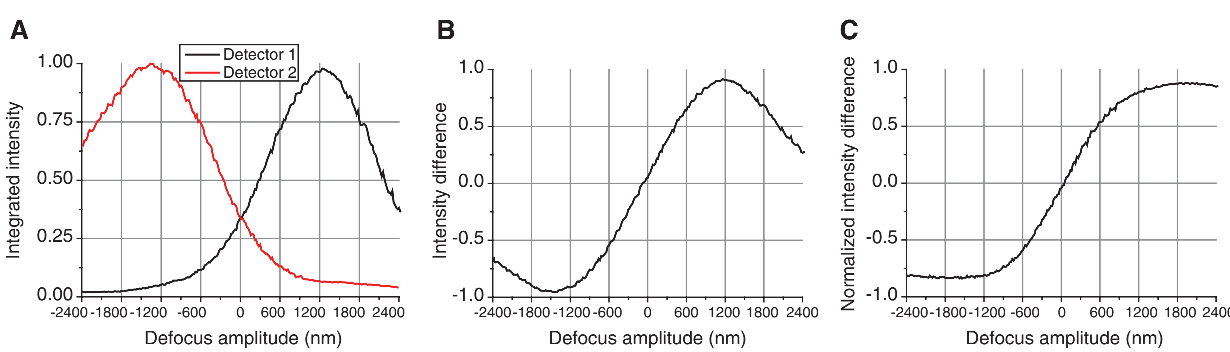

Figure 3 (A) The integrated intensities on the two detectors are shown as a function of defocus amplitude of the incoming laser beam. The difference of the spot intensities depends on the total intensity (B), but the normalized difference of the spot intensities is independent of the total intensity (C).

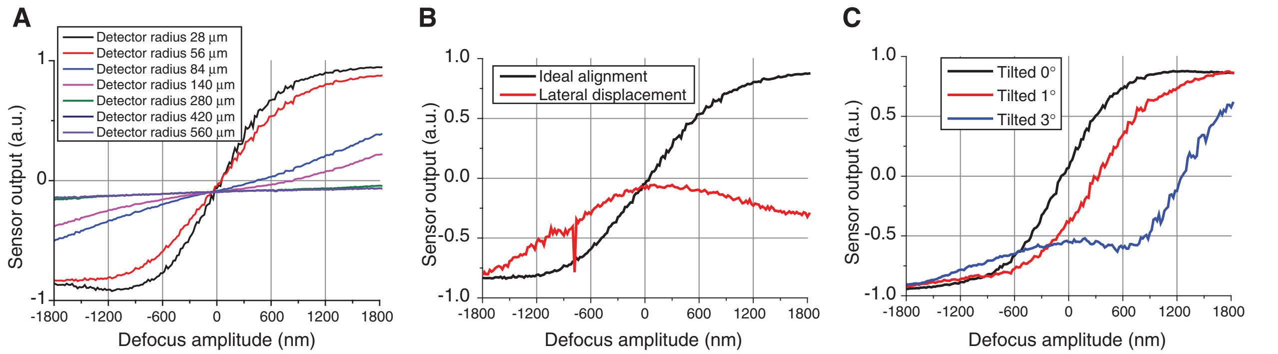

Figure 4 (A) The output of the sensor depends on the integration area of the detector. (B) Dependence of the HWFS response curve on the lateral displacement of the incoming laser beam. (C) Tilted incoming beam leads to incorrect measurement results for defocus.

respectively) was about 50 µm. It can be seen that the sensitivity of the HWFS will be significantly degraded when one increases the radius of the integration area by only 50% of the diffraction-limited spot, from 56 µm (red line) to 84 µm (blue line). On the other hand, such an increase in detector size might be necessary when dealing with residual tip/tilt error, and/or working at very high speeds and in noise-limited light regime.

Overall, beam wander and tilt are major problems for the HWFS. The effect of the aberration tip/tilt in the incoming beam on the HWFS has three components: First, the beam direction differs from the optical axis so the light is not diffracted exactly into the positions A^+ and A^-; instead, the focus spots are reconstructed at different locations. This offset from the optical axis influences the detectable intensities; small spot detectors could lose the signal completely. The second component is a lateral beam shift, which occurs with respect to the HOE. As a result, the reconstruction wavefront cannot match the reference wavefront. Therefore, the intensities of the reconstructed spots do not increase or decrease symmetrically together with changing defocus amplitude of the reconstruction beam. Figure 4B shows that, in this case, the sensor output does not contain usable information (red line). The third aspect to be considered is the tilt with which the wavefront reaches the diffraction pattern of the HOE. Compared to this pattern, the wavefront is compressed in one direction. This also leads to a mismatch and to incorrect measurement results (see Figure 4C). The influence of the first error component, the modified beam direction, was removed from the results presented here. This was done by adapting the optical axis and moving the spot detectors accordingly.

These measurements confirm the assumption that tip/tilt has to be significantly suppressed before using the HWFS.

4 Conclusions

The holographic wavefront sensor is a promising alternative to the Shack-Hartmann sensor for adaptive optics applications in challenging conditions, e.g., free-space laser communications. This new sensor type can reach MHz bandwidths and is, in principle, independent of scintillation. The sensor's response could be used together with the analytic relationships [11] or as a lookup table to deduce the amount of the measured aberration contained in the incident wavefront. The sensitivity of the HWFS is highly dependent on the detector size. We showed that an integration area of the order of the aberration-free spot provides best results. We also showed that the HWFS relies on tip/tilt precorrection.

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