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The Subaru Coronagraphic Extreme AO Project

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Subaru Telescope

Abstract. High contrast coronagraphic imaging is a challenging task for telescopes with central obscurations and thick spider vanes, such as the Subaru Telescope. Our group is currently assembling an extreme AO bench designed as an upgrade for the newly commissionned coronagraphic imager instrument HiCIAO, that addresses these difficulties. The so-called SCExAO system combines a high performance PIAA coronagraph to a MEMS-based wavefront control system that will be used in complement of the Subaru AO188 system. We present and demonstrate good performance of two key optical components that suppress the spider vanes, the central obscuration and apodize the beam for high contrast coronagraphy, while preserving the throughput and the angular resolution.

Keywords: Technique:Interferometry, Adaptive Optics

INTRODUCTION

In the first phase of the SCExAO project (spring 2010), a high performance PIAA coronagraph will be implemented with a MEMs-based wavefront control as an upgrade that will feed Subaru's newly commissioned coronagraphic imager instrument HiCIAO [1] in the context of the Subaru Strategic Exploration of Exoplanets and Disks (SEEDS) campain. SCExAO [2] uses a unique combination of advanced pupil remapping techniques: the Phase Induced Amplitude Apodization (PIAA) Coronagraph [3, 4] apodizes the pupil and removes the central obscuration of the beam, and a Spider Removal Plate (SRP) almost eliminates the diffraction spikes created by the spider vanes. While the achieved raw contrast level ($\sim 10^5$) in an Extreme-AO system is mostly driven by the speed and accuracy of the wavefront control system, the coronagraphic approach described in this paper and adopted for SCExAO will permit to achieve this raw contrast level at angular separations down to 1 λ/D.

LOSSLESS APODIZATION

On the Subaru Telescope pupil, the size of the central obstruction (30 %, linear) and spider thickness (22cm) require that the coronagraph is designed to remove the diffraction features they create in the focal plane. The spiders, if left uncorrected, create 4 spikes at $\sim 10^3$ contrast. These spikes are especially problematic at small angular separation, where they cover most of the position angle space. The central obscuration, at 30 %, creates its own set of diffraction rings with a 10^3 contrast level at the peak of the central obstruction's first ring (approximately 10 λ/D). Any coronagraph designed to offer contrast better than 10^3 on Subaru Telescope therefore needs to take into account the spiders and central obstruction.

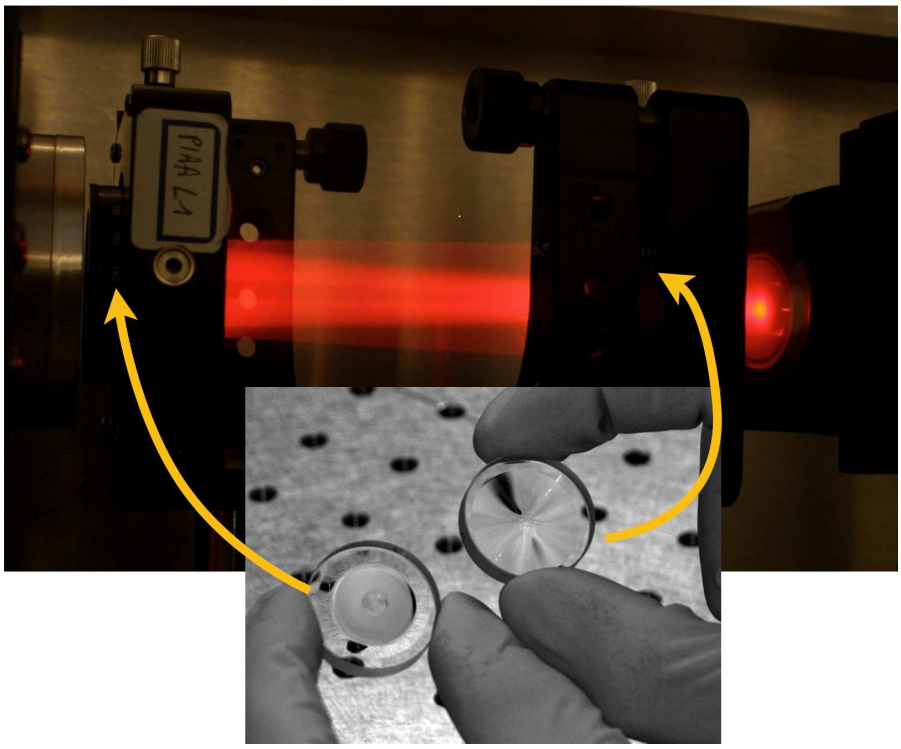

FIGURE 1. Apodization of the beam by the PIAA lenses, a core component of the SCExAO bench. The lens L_1 (on the left), changes the distribution of light in the pupil plane and L_2 (on the right) compensates the distortions of the wavefront L_1 introduces. Notice that as the light travels from left to right, the central obscuration of the telescope disappears and the pupil gets apodized, ready for high-performance coronagraphy.

PIAA with central obscuration

The simplest way of performing an apodization is to insert a mask whose radial transmission profile follows a prolate spheroidal function, the so-called classical pupil apodization (CPA). While extremely robust, and insensitive to moderate tip-tilt residuals, this approach has two main drawbacks: the throughput is low (as low as ~ 0.1 for a 10^{-10} contrast [5]), and the effective pupil diameter is reduced by a factor approximately equal to the square root of the throughput (due to the fact that apodizers remove the light mostly at the edges of the pupil), which translates into a loss of angular resolution.

The Phase Induced Amplitude Apodization (PIAA) [3] addresses these issues and apodizes the beam using a very different approach. It uses a set of two tailored optics working in pair: inserted in the pupil plane, the first (L_1 on Fig. 1) changes the distribution of light, while the second (L_2) collimates the beam for an on-axis source. The design retained for the SCExAO upgrade (cf. Fig. 1) suppresses the central obscuration.

Unlike CPA that discards light, the PIAA redistributes it across the pupil and therefore preserves the throughput and the angular resolution. Its main drawback is however the introduction of large aberrations for off-axis sources, an issue we address toward the end of the paper.

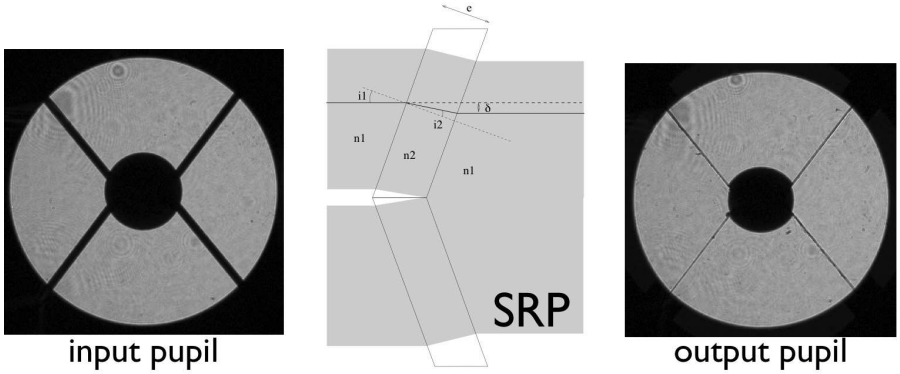

FIGURE 2. Suppression of the spider vanes by the SRP. The four quadrant defined by the spider vanes of the Subaru Telescope pupil (left panel) are translated inward by the SRP, using straightforward geometric optics (central panel). In the output pupil (right panel), the spider vanes are considerably reduced so that the diffraction spikes they create won't affect the SCExAO contrast performance.

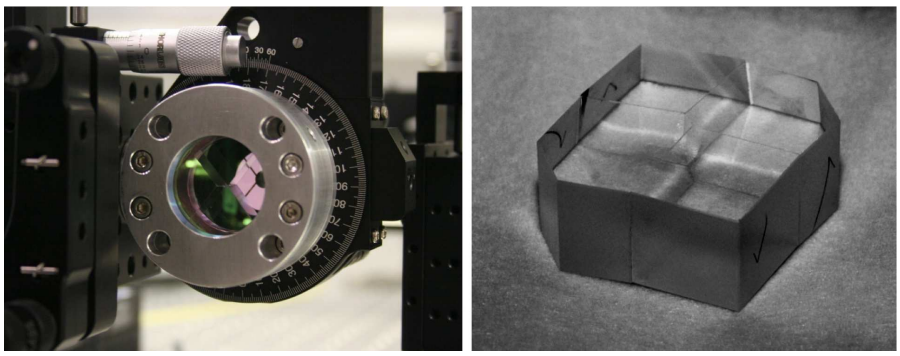

FIGURE 3. Left-hand panel: SRP in its mount on the SCExAO bench; Right-hand panel: close-up of the assembled SRP. The plate is 15 mm thick. Note that since the spider vane angle is not 45°, the SRP is not continuous at the interface between the four plates.

Removing the spider vanes

To suppress the diffraction by the spiders, our approach (Fig. 2), is to translate each of the four parts of the beam with a single tilted plate of glass to fill the gap due to the spiders. The spider vanes of the Subaru Telescope are 224 mm thick, for a total pupil diameter of 7.92 m. The SRP (Spider Removal Plate) consists of four tilted plane-parallel plates, each translating a part of the pupil inwards, as shown in Figure 2. It can be best described as a "pyramid-shaped rooftop" (cf. Fig. 3) of constant thickness. All four plates were cut from the same plane-parallel plate (a.k.a. optical window), to guarantee, within tolerances, a constant thickness.

For a window of thickness $e = 15$ mm and index $n = 1.443$ (Fused Silica for $\lambda = 1.6\mu$m), each plate needs to be tilted by an angle $\alpha = 5.004 \pm 0.02°$, to guarantee the continuity of the wavefront on-axis after remapping within $\lambda/10$.

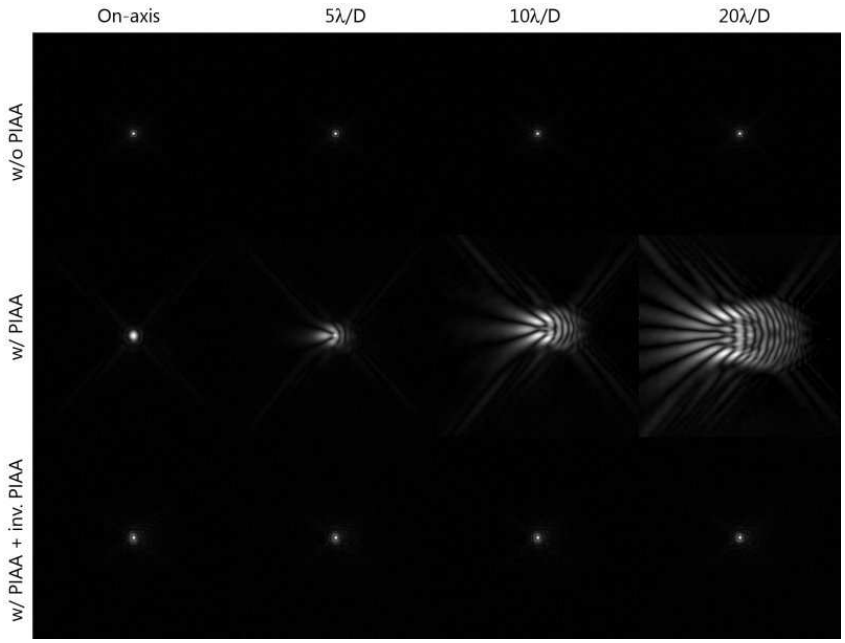

FIGURE 4. Series of off-axis images taken with the SCExAO system in the lab. These images show that the inverse PIAA (bottom row) efficiently corrects the huge aberrations the PIAA introduces in the first place (middle row), and turns the pineapple-shaped off-axis images into more conventional Airy-like images, virtually identical to the ones the system produces with no beam apodization at all (top row).

Recovering the field of view

For an off-axis source, the pupil-remapping the PIAA performs introduces large aberrations to the wavefront, which translate into very unsually shaped PSFs. The matter is not new and has been extensively described by Guyon et al. [4] in the case of a non-obstructed aperture. The novelty in the SCExAO PIAA is that it completely suppresses the central obscuration. This however requires a somewhat brutal remapping, with dramatic consequences on the PSF which finds itself pineapple-shaped at separations greater than 10 λ/D (cf. Fig. 4, middle row). Fortunately, just like with any pupil remapping [3], the aberrations the PIAA introduces can entirely be corrected using an exact copy of the PIAA, after the focal plane mask, only plugged backwards, which restores the original pupil and provides wide field of view imaging capabilities. Fig. 4 (bottom row) demonstrates the spectacular efficiency of the inverse PIAA.

REFERENCES

1. K. W. Hodapp, R. Suzuki, M. Tamura et al, "HiCIAO: the Subaru Telescope's new high-contrast coronographic imager for adaptive optics," 2008, vol. 7014 of *SPIE Conference Series*.
2. J. Lozi, F. Martinache, and O. Guyon, *ArXiv e-prints* (2009), 0903.5001.
3. O. Guyon, *A&A* **404**, 379–387 (2003), arXiv:astro-ph/0301190.
4. O. Guyon, E. A. Pluzhnik, R. Galicher, F. Martinache, S. T. Ridgway, and R. A. Woodruff, *ApJ* **622**, 744–758 (2005), arXiv:astro-ph/0412179.
5. O. Guyon, E. A. Pluzhnik, M. J. Kuchner, B. Collins, and S. T. Ridgway, *ApJS* **167**, 81–99 (2006).