# The Subaru Coronagraphic Extreme AO Project: progress report

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## ABSTRACT

In 2009 our group started the integration of the SCExAO project, a highly flexible, open platform for high contrast imaging at the highest angular resolution, to be inserted between the coronagraphic imaging camera HiCIAO and the 188-actuator AO system of Subaru. In its first version, SCExAO combines a MEMS-based wavefront control system feeding a high performance PIAA-based coronagraph, that suppresses the central obscuration and the thick spider vanes while preserving throughput and angular resolution. It also includes a coronagraphic low-order wavefront sensor, a non-redundant aperture mask and a visible imaging mode, all of them designed to take full advantage of the angular resolution (40 mas in the H-band) that an 8-meter telescope has to offer.

## 1. INTRODUCTION

The Subaru Telescope has recently commissioned a high-performance camera called HiCIAO,[1,2] to be used with its 188-element curvature-based Adaptive Optics (AO) system called AO188. HiCIAO was specifically designed in order to complete the Strategic Exploration of Exoplanets and Disks (SEEDS), an ongoing 120 night observing program conducted at Subaru.[3] The system performs remarkably well and was for example, able in little time, to detect planetary mass candidates (PMC) companions around the high proper motion star GJ 758.[4]

The last ten years of extrasolar planet research have been dominated by indirect detections techniques of radial velocity (RV) and photometric transit. The observational bias of these techniques initially led to the discovery of a large population of short period planets, exhibiting surprisingly diverse dynamics. Only as the time baseline increases, do RV and transits become more and more sensitive to long period planets of wide orbital separation.[5] At the other end of the parameter space, the detection limits of direct imaging, attributable to the partial correction of the wavefront by AO systems, has led to an unexpected handful of PMCs located at orbital separations so large (up to 300 AU[6]), that no current planet formation theory can really justify their existence, without some serious tweaks.

The detection of high-contrast companions in AO images is limited by the presence of residual speckles, attributable in part to non-common path errors between the wavefront sensing arm and the final detector (the so-called "quasi-static" speckles), and in part to the ever changing atmosphere generating short lived speckles. Of the two, the quasi-static component is the more harmful[7] and can only be mitigated using post processing techniques like Angular Differential Imaging.[8,9] Yet ADI can only efficiently probe for PMCs at angular separations greater than 0.5 arc second, and reach maximum sensitivity around 1 arc second. Even for the nearest populations of young stars, at distances of 30 parsecs, these detection limits translate into projected orbital separations greater than 30 AU.

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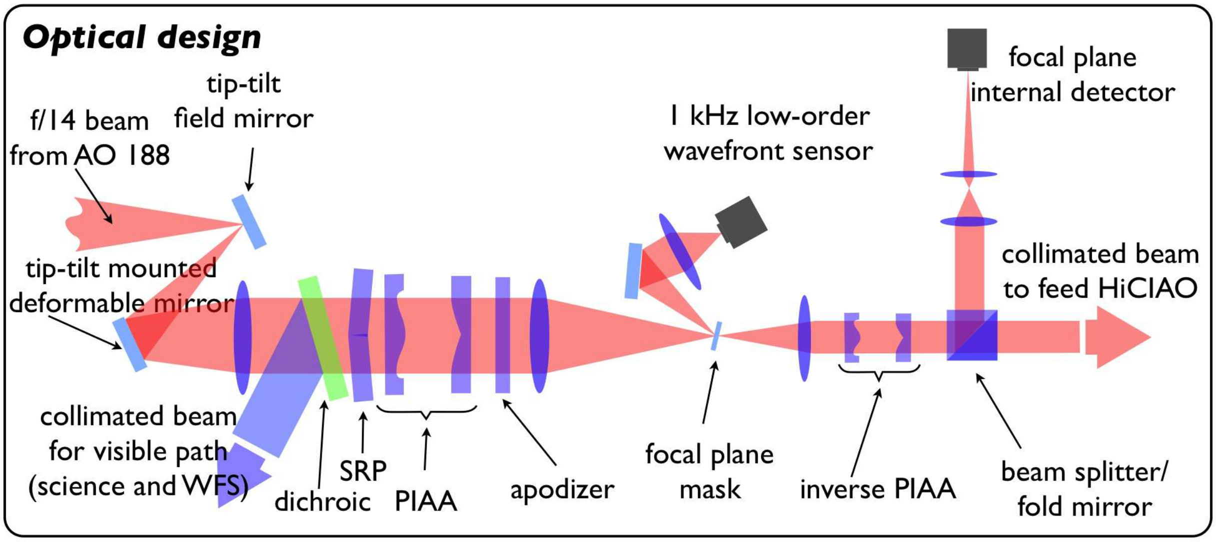


Figure 1. Optical design of the SCExAO bench. The light travels from the left (AO188 side) to the right (HiCIAO side), bounces off the DM located in a divergent beam, and is collimated before being shaped by the SRP and the hybrid PIAA, for high contrast coronagraphy. The focal plane mask reflects part of the on-axis source light toward the Coronagraphic Low-Order Wavefront Sensor camera. Anything else reaches the science camera HiCIAO after being de-apodized by the inverse PIAA.

To fill up the gap between the RV+transit PMC population and the AO imaging PMC population requires a new approach. The current 8 to 10 meter generation of telescopes provides sufficient angular resolution in the near IR ($\lambda/D = 40$ mas for a 8 meter telescope observing at $1.6\,\mu m$), to even probe the Habitable Zone of most nearby systems, but one needs to compose with the fundamental limit of diffraction. This regime is already being explored, thanks to the technique of non-redundant masking (NRM) interferometry that is sensitive to the high mass end of the PMC population.[10] Quite remarkably, masking achieves this by filtering out low-order wavefront aberrations in a very passive manner, only at the cost of signal. To probe deeper, a more "active" approach is required and several projects of so-called extreme AO project are currently under development. This paper describes the Subaru Coronagraphic Extreme AO (SCExAO) project.

## 2. REQUIREMENTS FOR AN EXTREME AO SYSTEM

Figure 1 presents the so-called phase 1 optical design for the IR coronagraphic arm of SCExAO. The whole bench is built on a 1.2-meter long optical table, designed to be inserted between Subaru's 188-actuator AO system and the HiCIAO camera. For standalone use, the system is equipped with its own detector, a fast readout InGaAs camera (Xenics model XS-1.7-320), with an optical design that allow to image both pupil and image plane.

### 2.1 High order wavefront control

One of the key requirement is of course the addition of high-spatial frequency wavefront control capability. A MEMS-based kilo-actuator deformable mirror, despite its limited stroke ($\sim 1.5\mu m$), is perfectly suited if used in complement to a conventional AO system that produces diffraction limited images (i.e. wavefront residuals of smaller than $\lambda/4$) in the near infrared.

The number of available actuators across the full pupil defines the outer working angle (OWA) of the extreme AO correction. SCExAO employs a 32x32 actuator mirror, which constrains the OWA to $16\,\lambda/D$, that is approximately 0.5 arc second for Subaru at $\lambda = 1.6\mu m$. Within that narrow field, the DM can be used to in a couple different ways. The most obvious, is of course to perform an additional real-time wavefront correction to improve the overall image quality. This is however not something SCExAO will be able to do in the first phase of its deployment at the telescope since this also requires a fast wavefront sensor still at study.

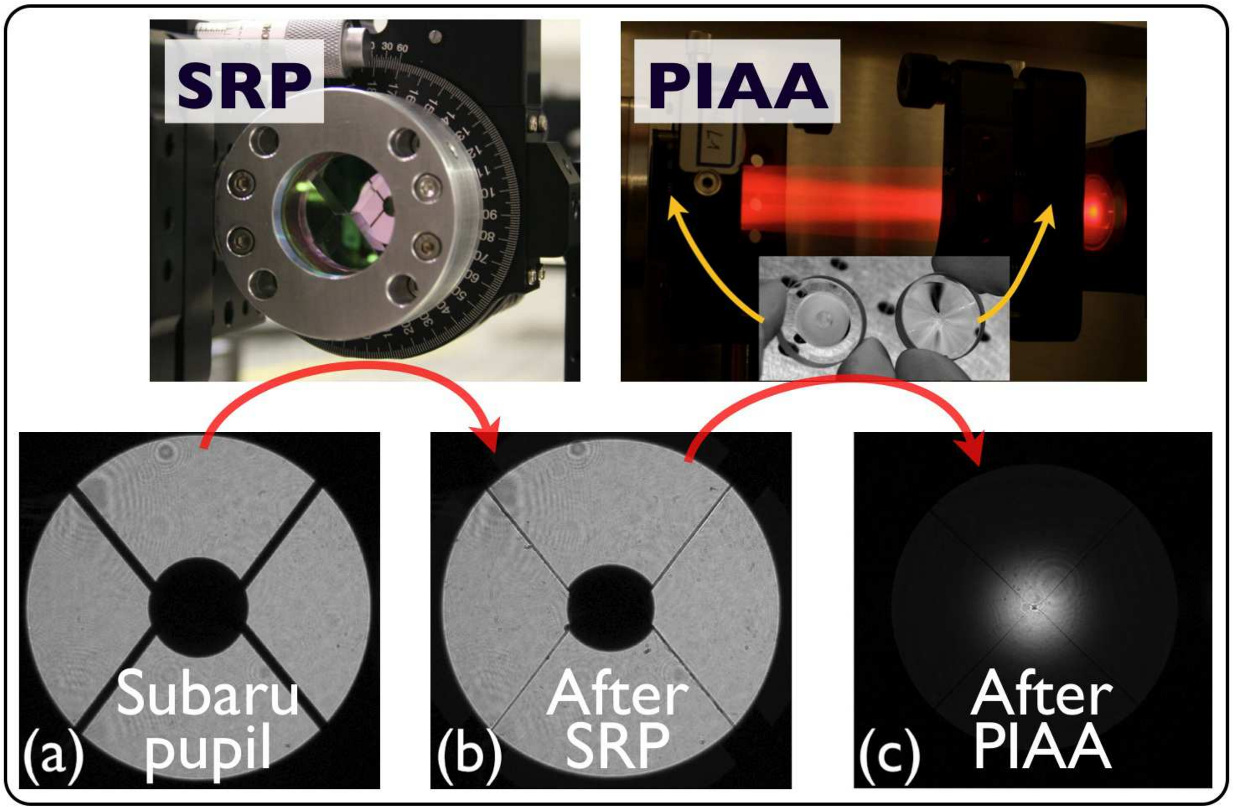


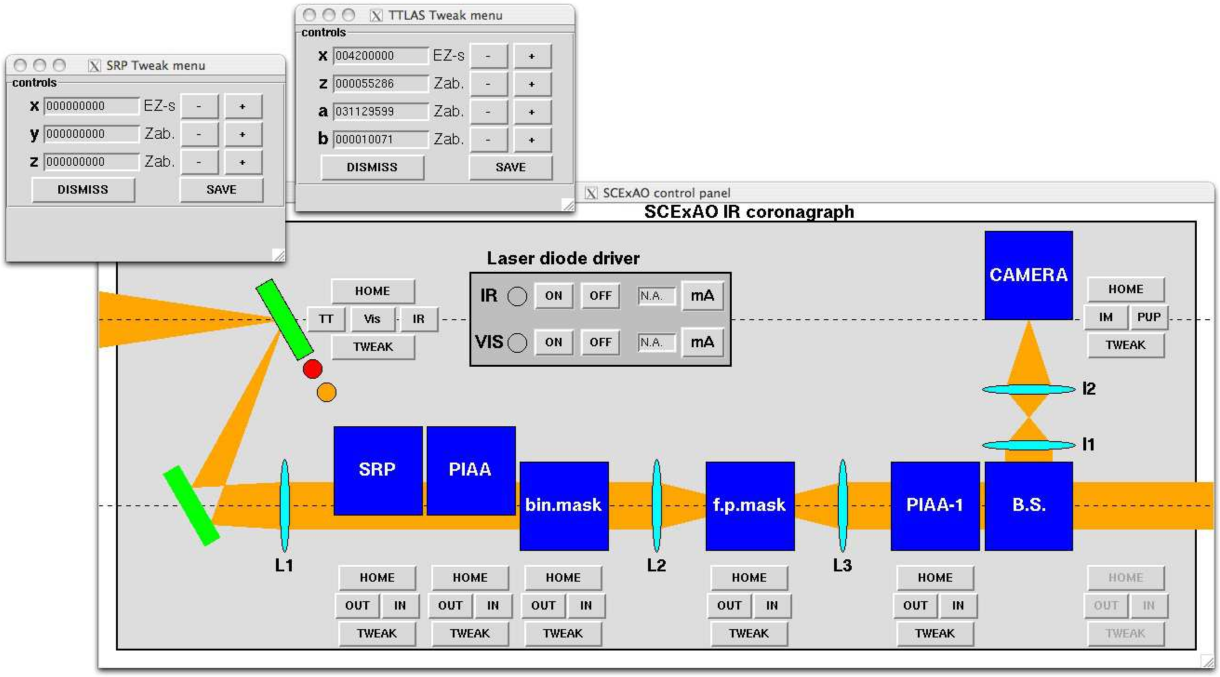
Figure 2. Demonstration of the pupil remapping by the special optics used in SCExAO. The Spider Removal Plate (SRP) reduces the diffraction spikes created by the spider arms of the Subaru Telescope pupil. The PIAA-based apodizer fills up the hole left by the central obscuration of the telescope and shapes the beam to reduce the Airy rings where the focal plane is located. This unique combination of optics turns the Subaru Telescope pupil into a very coronagraph friendly aperture, with negligible impact on throughput.

A fast rate correction is however not the most essential need to cover in phase 1. Indeed, a major contribution to the limits to the performance of AO imaging is the presence of non-common path errors between the wavefront sensing arm and the science imaging arm after a beam splitter. These non-common path errors, which are non-trivial and slowly changing with time are the reason behind the existence of the quasi-static speckles. To address these non-common path errors, one needs to perform the wavefront sensing at the level of the final science detector, where what is measured is exactly what needs to be calibrated. For this, the DM can be used to introduce a known phase diversity, and actively "probe" the speckles by measuring their coherence and discriminate them from potential close companions to the observed targets (see Guyon et al, this conference). This approach, used in laboratory conditions[11] has achieved $2 \cdot 10^{-7}$ raw contrast at 2 $\lambda/D$, that is several orders of magnitude beyond the SCExAO raw performance.

## 2.2 High-performance coronagraph

With a 30% central obscuration and thick spider vanes, the pupil of the Subaru Telescope is clearly incompatible with most high-performance coronagraphs. Even in the absence of aberrations, the diffraction spikes created by the spider vanes are a serious hindrance to the detection of high contrast companions at small angular separation. While these effects can be minimized after the focal plane mask by a well chosen Lyot-stop, this usually comes at the expense of throughput. On SCExAO, this issue is addressed with a custom device called the spider removal plate (SRP),[12] made of four tilted plane-parallel plates that geometrically remaps the pupil and reduce the diffraction by the spider vanes below SCExAO's detection limits.

The pupil is further made coronagraph friendly using a Phase Induced Amplitude Apodization (PIAA).[13, 14]


SRP Tweak menu

controls

x 000000000 EZ-s

y 000000000 Zab.

z 000000000 Zab.

TTLAS Tweak menu

controls

x 004200000 EZ-s

z 000055286 Zab.

a 031129599 Zab.

b 000010071 Zab.

SCExAO control panel

SCExAO IR coronagraph

Laser diode driver

IR N.A. mA

VIS N.A. mA

Figure 3. Screenshot of the SCExAO bench control GUI. All special optics of SCExAO: SRP, PIAA, binary mask, focal plane mask and inverse PIAA can be moved in and out of the beam. It is possible in just a few clicks, to turn SCExAO into a more conventional Lyot coronagraph.

The PIAA used on SCExAO carries out two tasks: it suppresses the central obscuration of the telescope and apodizes the beam for high-contrast coronagraphy. Unlike classical apodization techniques that use a mask of variable transmission profile, at the expense of throughput and angular resolution, the PIAA does this by redistributing the light with aspheric optics. SCExAO's PIAA coronagraph optics are designed to produce a $10^{-6}$ raw contrast PSF at $1\lambda/D$.[12] Figure 2 shows the dramatic effect of the pupil remapping by the SRP and the PIAA combined, without sacrificing either resolution or throughput.

## 2.3 Low-order wavefront control

Just like with a regular AO system, the control of low-order aberrations requires its dedicated sub-system. Indeed, the imaging of companions close to the edge of the occulting mask in a coronagraph is very sensitive to low order aberration modes such as pointing and focus. Of these aberrations, pointing is especially critical since a tip-tilt excursion along a given direction will exactly mimic the signal of a true companion at a small angular separation in a coronographic image.

This is a major concern for a system like SCExAO that is designed to attempt the detection of high contrast companions at small angular separation. To address this concern, SCExAO implements its version of the Coronagraphic Low-Order Wavefront Sensor (CLOWFS).[15] Using the central star light reflected by a custom focal plane mask, CLOWFS has demonstrated outstanding pointing error tracking precision in laboratory conditions (stability of the order of $10^{-3}\lambda/D$), and can also be used (cf. Vogt et al, this conference) to calibrate, in post-processing, tip-tilt induced coronagraphic leaks in the final science image.

## 2.4 Flexible evolutive design

Direct detection of extrasolar planets with ground based telescopes is a fast moving field, with new attractive coronagraph concepts still appearing regularly as the technology of optics manufacturing progresses: flexibility is therefore a requirement, and SCExAO's design is very modular, open to new concepts and ideas. One example is the idea of using a high performance eight-octant phase mask coronagraph.[16] Because this mask cannot be used

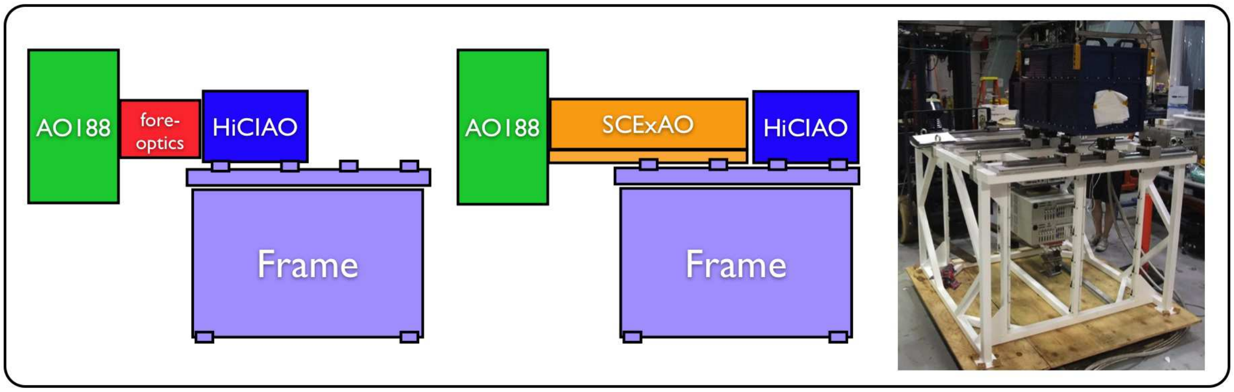


Figure 4. Left: different use cases for the required custom HiCIAO/SCExAO frame. SCExAO specializes in the study of very narrow field ($\sim 16\lambda/D$) and therefore cannot fully replace HiCIAO's current fore-optics. The frame is designed to welcome HiCIAO in two positions: in the front with its current fore-optics, and in the back with SCExAO. Right: picture of HiCIAO during fitting tests, sitting on the new frame in the front position, emulating the current "wide-field" HiCIAO+fore-optics configuration.

on a pupil with a central obscuration, we are considering (cf. Murakami et al, this conference) the construction of a new set of PIAA-like remapping optics that would only suppress the central obscuration, without apodizing the beam.

Figure 3 shows a scren capture from the GUI controlling the SCExAO bench that illustrates the flexibility of the design. Except for the relay optics that are necessary to the propagation of light from AO188 to HiCIAO, each element is mounted on a stage that can be taken in and out of the beam, already allowing to turn the full high contrast coronagraph into a conventional Lyot-coronagraph with a $4.75\,\lambda/D$ IWA.

SCExAO is designed as an additional very narrow field observing mode of the HiCIAO camera designed to take "wide-field" (20 arcsec) images of extended structures like disks. Not disrupting HiCIAO's regular observing modes required the development of a new highly configurable frame capable of hosting HiCIAO, SCExAO as well as other potential extensions like an IFU. Figure 4 shows the two primary uses of the frame: emulating HiCIAO's current observing mode with HiCIAO in front position, and in extreme AO mode with SCExAO replacing HiCIAO's coronagraphic fore-optics; as well as a recent picture of the frame taken during fitting tests with HiCIAO in front-position.

## 3. COMPLEMENTARY OBSERVING MODES

### 3.1 Diffraction limited imaging in the visible

In parallel of the IR arm, and in preparation for the visible wavelength fast wavefront sensor that will equip SCExAO in phase 2, the optical table is being complemented by a visible arm, designed to provide diffraction limited images between 0.6 and 0.85 $\mu m$. The split happens after the DM (cf. Fig. 1) with a dicroic filter that reflects the blue part ($\lambda = 900\,\mu m$) of the light, so that it also corrected both by AO188 and the DM.

This visible arm (not represented in Fig. 1) uses a fast readout EMCCD camera with a 90 % quantum efficiency, capable of acquiring at 1 kHz in a subarray mode that corresponds to a 0.6 x 0.6 arc second field of view. The initial data processing for this data is a Fourier-based statistical filter whose principle is described in Fig. 5. See Garrel et al, (this conference) for more information on this simple, yet very attractive observing mode of SCExAO.

### 3.2 Non-redundant masking interferometry

NRM interferometry was mentioned in the introduction of this paper as a method that already explores the regime of angular separation SCExAO will explore, at low contrast. In NRM, the full aperture of the telescope is masked, except for a finite number of holes (cf. Fig. 6), whose location is chosen so that each interferometric baseline they form is unique. This design makes it possible to extract phases and to calculate closure phases, an

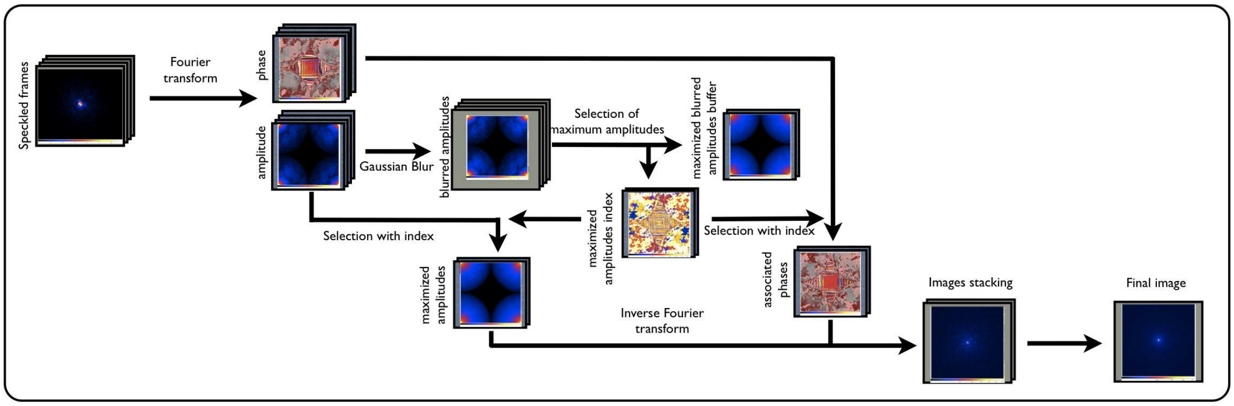


Figure 5. Schematic description of a Fourier-based statistical filter for the obtention of diffraction limited images with the visible arm of SCExAO.

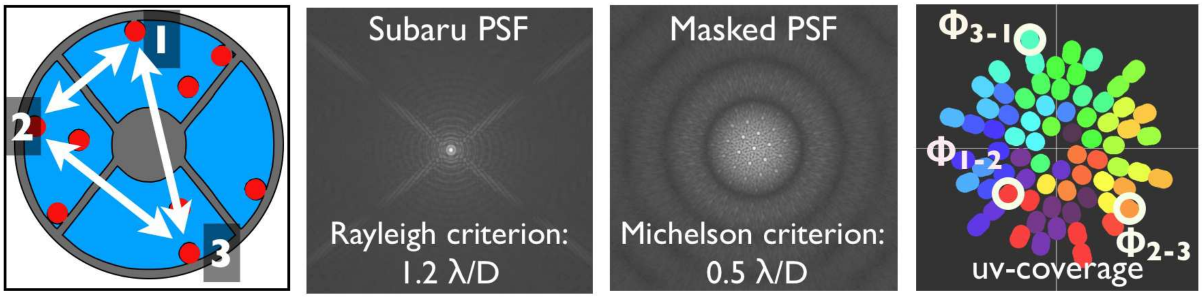


Figure 6. Non-redundant mask design for the Subaru Telescope pupil. The first panel shows the mask and highlights one possible baseline triangle along which a closure-phase relation can be built. The two central panels highlight the difference between the full pupil Subaru PSF and its masked counterpart. The last panel shows the corresponding $u, v$-coverage and highlights the location of the points corresponding to the baselines forming the selected closure triangle.

observable quantity that is immune to large scale structures of the wavefront. The high level of calibration of this quantity makes it possible to detect companions well within $\lambda/D$.[17]

The significant observing experience accumulated with NRM suggests that one key to the contrast limits is the variability of wavefront structures within each hole. With its large number of actuators, the SCExAO DM will allow to reduce these wavefront structures, ultimately leading to better calibration and higher contrast. SCExAO will therefore implement one such non-redundant mask, in the collimated beam located after the focal plane mask.

## 4. CONCLUSION

SCExAO is a in-house development designed to complete the parameter space of the ongoing SEEDS survey, by providing high contrast access to the 20 to 500 milli-arcsecond range of angular separation. To achieve this, SCExAO combines the elements that address the key issues that accompany this objective: a high-performance coronagraph with a high throughput and a small inner working angle, the wavefront control devices for low and high order aberrations with sensing happening at the level of the focal plane, completed by a visible diffraction limited imager and masking interferometry capability. Mechanical fittings tests of SCExAO at the Subaru IR Nasmyth floor as well as preliminary optical tests with AO188 will be conducted during Subaru's summer 2010 downtime. First light at the telescope is scheduled for the spring semester of 2011.

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