Wavefront control with the Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system

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ABSTRACT

The Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) system uses advanced coronagraphic technique for high contrast imaging of exoplanets and disks as close as 1 lambda/D from the host star. In addition to unusual optics, achieving high contrast at this small angular separation requires a wavefront sensing and control architecture which is optimized for exquisite control and calibration of low order aberrations. The SCExAO system was thus designed to include the wavefront sensors required for bias-free high sensitivity and high speed wavefront measurements. Information is combined from two infrared wavefront sensors and a fast visible wavefront sensors to drive a single MEMS type deformable mirror mounted on a tip-tilt mount. The wavefront sensing and control architecture is highly integrated with the coronagraph system.

Keywords: Exoplanets, Coronagraphy

1. OVERVIEW OF THE SCEXAO SYSTEM

1.1 System goals and architecture overview

SCExAO is designed as a highly flexible instrument for high contrast imaging. It consists of an optical bench, inserted between Subaru Telescope facility adaptive optics system and HiCIAO, a near-IR camera specifically designed for high contrast imaging. The SCExAO bench includes the coronagraphic optics and wavefront control required to obtain high contrast images with the HiCIAO camera.

SCExAO is optimized for high contrast imaging at small angular separation, and uses new techniques to achieve this goal. There is a strong scientific motivation for providing this capability:

- The number of exoplanets that can be imaged rises steeply as the coronagraph inner working angle (IWA) is reduced, as the number of targets around which a particular type of planet is accessible scales as the inverse third power of the IWA. SCExAO is designed to reach 1 λ/D IWA, this being able to access 8 times more planets than a system with a 2 λ/D IWA system.
- Access to small IWA can potentially allow direct imaging of exoplanets in reflected light: reflected light scales as the inverse square of distance from the star.
- With a 1 λ/D IWA on a 8-m telescope, protoplanetary and debris disks can be imaged in the star's habitable zone, therefore putting strong constraints on the formation and evolution of habitable planets

The high contrast performance is obtained by combining a high performance coronagraph, wavefront control, and calibration of residual light in the image. The SCExAO system hardware is briefly discussed in this section, while the rest of the paper is focused on SCExAO's wavefront control architecture. Other papers in this conference describe the SCExAO implementation in more detail.

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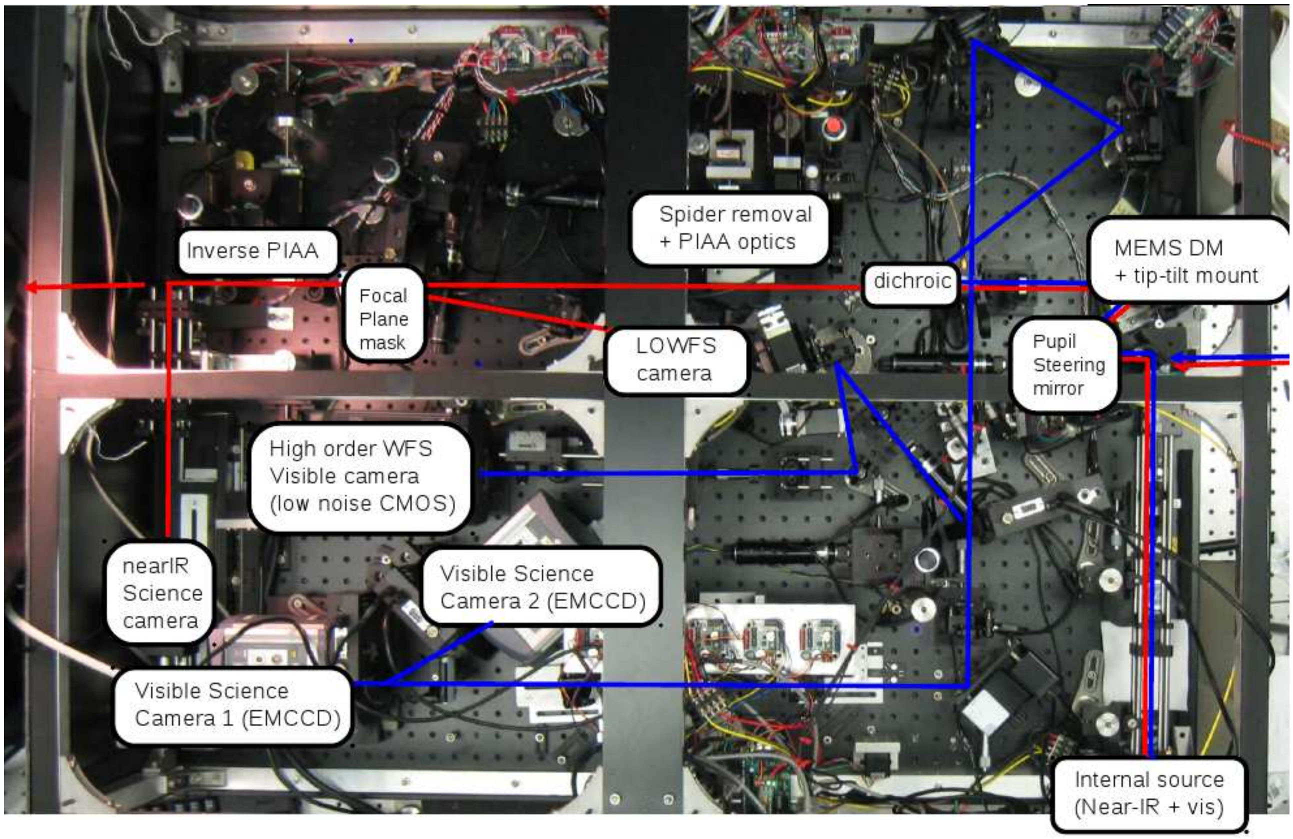

Figure 1. Top view of the SCExAO optical bench. SCExAO is the first ground based coronagraph system using a PIAA, and is used on the 8.2-m Subaru Telescope. Light coming from Subaru's facility AO system enters from the right of the picture, and exits at the left corner to be fed to the HiCIAO differential imaging camera.

1.2 Coronagraphy

SCExAO relies on Phase-Induced Amplitude Apodization (PIAA) to produce high contrast images at small angular separation. The PIAA technique uses aspheric optics to reshape the telescope beam into an apodized beam with no loss in throughput or angular resolution.[1,2] This coronagraphic approach offers very high performance, as it combines full throughput, small IWA and uncompromized angular resolution. At the 1e-6 raw contrast level for which the optics were designed, the IWA is 1 λ/D. The PIAA optics are used to produce an image free of diffraction rings in the coronagraph focal plane. A mask then removes starlight, leaving light from other sources (planets, disks) largely unperturbed. The strong remapping performed by the PIAA optics produces large PSF aberrations for off-axis sources. A set of inverse PIAA optics is thus required at the back end of the coronagraph to cancel field aberrations introduced by the first set of PIAA optics. This inverse set plays no role in the coronagraphic process, but considerably extends the field of view over which the PSF is diffraction limited.

1.3 Implementation

Figure 1 shows a top view of the SCExAO coronagraph bench, illustrating the fact that, for such a system, wavefront control is at least as large a part of the effort as are the coronagraph optics (which occupy a very small fraction of the optical bench). SCExAO is the first ground based coronagraph system using a PIAA, and is used on the 8.2-m Subaru Telescope.

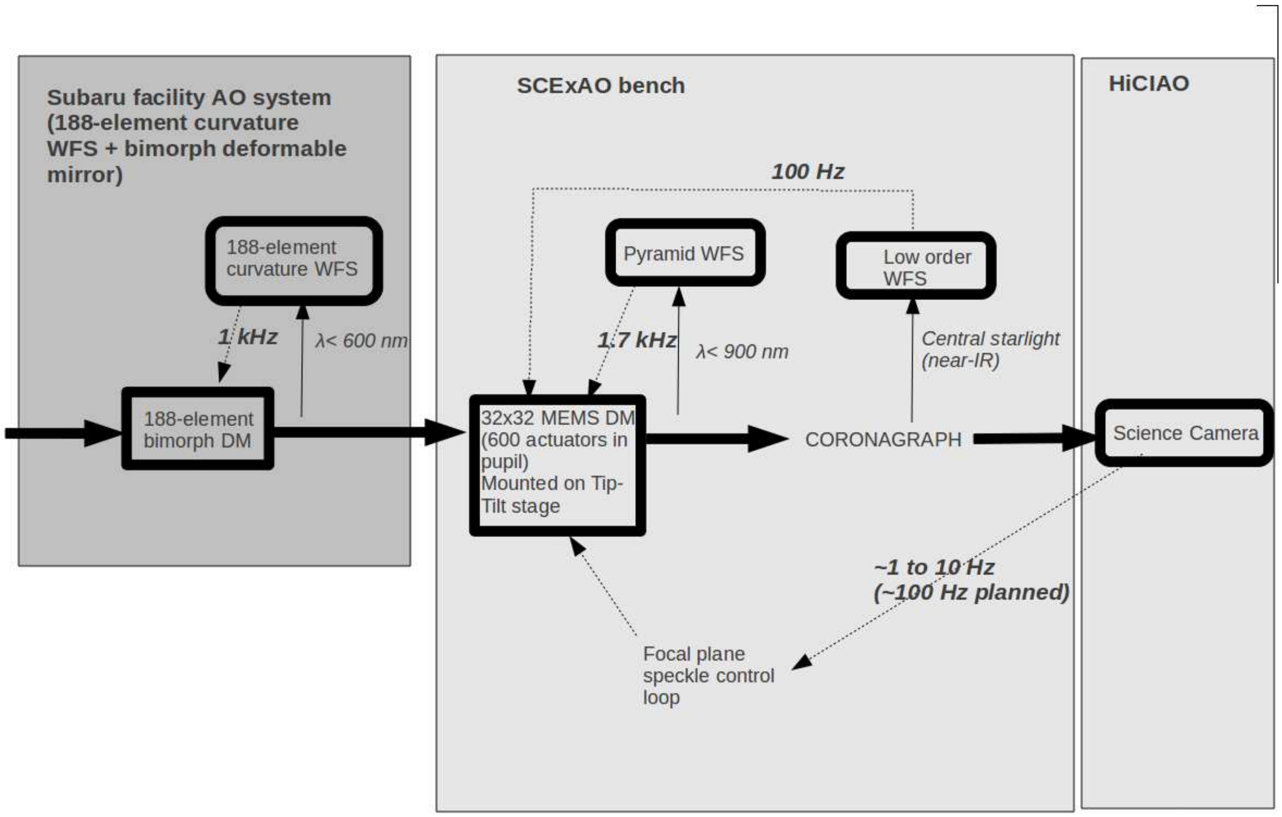

Figure 2. SCExAO wavefront control architecture. The full system is composed of the facility AO system (left), the SCExAO bench (middle) and the HiCIAO camera (right), and includes 4 wavefront sensors (rounded boxes) and two deformable mirrors (square boxes). Light path is shown with solid arrows, and control signals are shown with dashed arrows.

2. WAVEFRONT CORRECTION GOALS

The wavefront control approach for SCExAO is shown in figure 2, and can be understood as fulfilling four essential goals/functions:

1. First, the wavefront RMS phase should be reduced as much as possible to reduce the surface brightness of the atmospheric speckle halo
2. Low order aberrations need to be very well controlled, as they can easily compromise high contrast imaging at small angular separation
3. Static diffraction and slow speckles need to be removed in the science image, as they will otherwise amplify speckle noise
4. A robust calibration scheme must separate residual starlight from true companions, disks

Each of these four functions is described in the following four sub-sections.

2.1 Reducing wavefront RMS phase

The first step in achieving high contrast imaging is to reduce the speckle halo surface brightness, which is a noise for detection of planets and disks in the image (speckle noise and photon noise). This is achieved by conventional adaptive optics technique(s), aimed at reducing the residual phase errors in the pupil plane. SCExAO takes

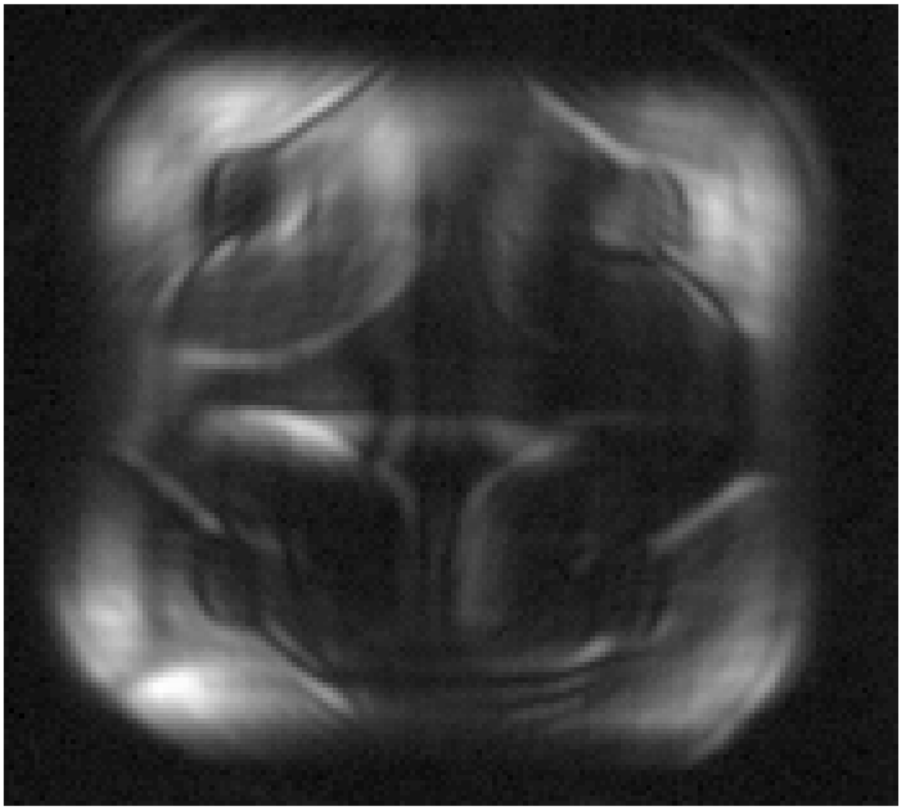

Figure 3. Sample image obtained in the laboratory with SCExAO's pyramid WFS. The 128x128 pixel image is extracted from a 128x144 pixel window read at 1.7 kHZ frame rate.

advantage of the initial correction provided by the facility adaptive optics, which delivers to the SCExAO bench a diffraction-limited in near-IR. The facility AO system is however not optimized for extreme-AO, and the SCExAO bench thus includes a high order fast and sensitive wavefront sensor working in visible light. We have adopted the pyramid wavefront sensor[3] concept for this. A CMOS-based camera reads a 128x144 pixel window of the detector at 1.7 kHZ with a 1e- readout noise. A sample image from the SCExAO pyramid WFS is shown in figure 3. SCExAO's 32x32 actuators MEMS is used for wavefront correction.

To obtain maximum sensitivity, the SCExAO pyramid WFS is non-modulated. This offers diffraction-limited sensitivity for low order modes, which is very desirable for high contrast imaging, but, as shown in figure 3, also produces diffraction effects in the sensor. The wavefront solution does therefore not follow the simple wavefront slope linear dependence found in modulated pyramid, and our wavefront reconstruction algorithm must take diffraction into account. Operating a pyramid WFS in this highly sensitive regime is possible thanks to the initial wavefront correction provided by the facility AO system: wavefront excursions are kept small, therefore ensuring that the non-modulated pyramid WFS produces a signal of sufficient quality to close the extreme-AO loop.

The pyramid WFS in SCExAO is currently part of the SCExAO bench and is running in open loop (data acquisition only, no real-time wavefront reconstruction), as we are developing the wavefront reconstruction algorithm.

2.2 Control of low order aberrations

Small IWA coronagraphic imaging is unusually demanding in wavefront control of low order aberrations (tip, tilt and focus). These aberrations produce significant light leak around the edge of the coronagraph focal plane mask, where the SCExAO system is aimed at providing high contrast imaging. Our approach to actively controlling these aberrations relies on:

- Using of a visible extreme-AO wavefront sensor which is highly sensitive to low order aberrations. The pyramid WFS, when non-modulated, is an ideal choice for this, as described in the previous subsection
- Using a dedicated near-IR low order wavefront sensor which extracts light from the coronagraph's focal plane mask

These two sensors work together to measure low order aberrations, and are highly complementary. The pyramid WFS is both very sensitive and fast (operates at 1.7 kHz), but may suffer from non-common path errors, as it is not located in the coronagraph path and is using visible light while the coronagraph operates in near-IR. The coronagraphic low-order wavefront sensor[4] (LOWFS) is slower, but is free of non-common path error and provides the accurate reference needed for control of the low-order aberrations. Combining the slow temporal frequency signal derived from the LOWFS with the high temporal frequency signal obtained with the pyramid WFS provides adequate control of low order aberrations for high contrast imaging.

2.3 Removing slow and static speckles

In section 2.1, we pointed out the importance of reducing the level of fast atmospheric speckles in the PSF. It is also equally important to remove static and slow diffraction features in the focal plane image, not only because these features contribute to photon noise, but also because they can interfere with residual atmospheric speckles and therefore coherently amplify speckle noise. Our approach to solve this problem is twofold

- **Coronagraphy**. Known static diffraction features (diffraction from the telescope aperture) are removed by the coronagraph, which is designed to passively remove these features to the 1e-6 contrast level.
- **Focal plane speckle control**. Unknown static and slow diffraction features (due to imperfection in optics, or slow speckles in the image) are removed by the MEMS deformable mirror, and are measured directly from the coronagraphic science image. This technique, originally developed for high contrast imaging from space,[5] was tested on a PIAA-based coronagraphic system similar to SCExAO's architecture,[6] and its implementation on SCExAO is similar to this previous demonstration.

The speckle control technique uses the MEMS DM to probe speckles (measure their complex amplitude), and uses the same DM to them remove them from the image by adding to them antispeckles which destructively interfere with the speckles.

2.4 Calibration

Calibration of residual light in the coronagraphic image is performed by several techniques in SCExAO:

- Passive calibration using spectral, angular or polarimetric differential imaging
- Active calibration using coherence as a discrimination tool. The speckle control technique described in section 2.3 also serves as a coherence sensor, measuring how light in the focal plane image interferes with starlight. While light due to residual wavefront error will interfere with the light added by the DM modulation, the light from a planet would not interfere.
- Post-processing using telemetry from SCExAO's wavefront sensors. The measurements performed by the pyramid and LOWFS sensors are stored, and used to estimate the amplitude and distribution of residual starlight in the science focal plane.

3. CONCLUSION

The SCExAO system wavefront control architecture is aimed at supporting high contrast imaging in the 1 to $\approx$ 10 λ/D angular separation, which is made available by the use of a high performance PIAA type coronagraph. To do so, several new techniques (non-modulated pyramid WFS, coronagraphic LOWFS, speckle control using focal plane image), with high expected payoff, are employed, making good use of the flexibility offered by the SCExAO architecture. SCExAO is thus expected to be both a scientifically unique and productive instrument, and a testbed for new high contrast imaging techniques. With on-sky observations currently starting, we expect that much will be learned about the value and performance of these new techniques.

ACKNOWLEDGMENTS

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