

# Multi-Star Wavefront control with SCExAO instrument: demonstration with an internal source

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## ABSTRACT

Although only a small fraction of currently known exoplanets was found in binary and multiple systems, studies show that such stars do form planets, with an efficiency that is smaller, but within an order of magnitude of single stars. However, binaries are rarely considered as targets for exoplanet imaging space missions because of challenges of removing light from the second binary component.

In our previous works it was shown how to solve two main issues that make exoplanet imaging in multiple systems impossible, namely, the mutual incoherence of speckles created by different binary components, and inability of a deformable mirror (DM) to control the starlight beyond the DM outer working angle/Nyquist limit. Feasibility of the developed Multi-Star Wavefront Control (MSWC) and Super-Nyquist Wavefront Control (SNWC) algorithms was demonstrated at the Ames Coronagraph Experiment (ACE) laboratory using a simple imaging system with a DM and no coronagraph.

In this paper, we report the results our MSWC experiments using the Subaru Coronagraphic Extreme Adaptive Optics (SCExAO) instrument that is part of our technology development effort. The main goal of these experiments is to validate MSWC on a real coronagraphic system by using an internal source to simulate at least one real representative binary target. In our demonstration narrow-band contrast of  $4.1 \times 10^{-6}$  has been reached by using MSWC in a  $12 \times 6\lambda/D$  dark zone separated from the primary component of the simulated binary star (STF 3121 AB) by  $4\lambda/D$ . This contrast is better by a factor of 13.2 than the contrast floor reached by standard single-star wavefront control (SSWC). We also discuss the main limiting factors that affect the MSWC performance in our experiments.

**Keywords:** Exoplanets, Coronagraphy, Multi-Star Wavefront Control

## 1. INTRODUCTION

Stellar multiplicity plays an important role in many areas of astronomy, and the study of exoplanets is no exception. Approximately 20% of M dwarfs are combined in binary and multiple systems<sup>1</sup> and the multiplicity factor for F–G dwarfs reaches 46%.<sup>2</sup> The observed rate of the exoplanet host stars that have a stellar component varies between 12% and 23%<sup>3–7</sup> (depends on the used sample). It means that a large fraction of exoplanets in binary/multiple systems are still waiting to be discovered and studied. The closest of these binaries probably could be observable with the largest ground based telescopes, but the appropriate observational techniques should be developed.

The interest for the exoplanets in the binary/multiple systems is continuously growing and inspired by regular discoveries of new exoplanets in binary/multiple systems. Among the nearest binaries/multiple systems with exoplanets are such systems as Kepler 47,<sup>8</sup> Proxima Cen,<sup>9</sup> probably  $\alpha$  Cen<sup>10</sup> (unconfirmed). Currently, 268 exoplanets are detected in 189 binary and multiple systems.<sup>11</sup> At the same time, binaries are rarely considered as targets for exoplanet imaging surveys because of challenges of direct high contrast imaging in such systems.

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Though the light from one of the binary components can be easily suppressed by the commonly used single star wavefront control (SSWC) methods, the incoherent (relative to the first star) speckles formed by the second star remain uncorrected. To overcome the light leakage from the second star, simultaneous wavefront control is needed, that removes these secondary speckles. Such a method, the so called Multi-Star Wavefront Control (MSWC), was introduced<sup>12</sup> together with its extension super-Nyquist Wavefront Control (SNWC). The SNWC enables the light suppression beyond the nominal Nyquist region of the deformable mirror (DM) and allows high contrast imaging for wide visual pairs inaccessible by standard wavefront control. Both methods can be implemented with almost any coronagraph, including those designed for NASA's flagship missions such as Roman, HabEx, and LUVOIR.<sup>13</sup>

Feasibility of sub-Nyquist and super-Nyquist wavefront control was earlier demonstrated at the Ames Coronagraph Experiment laboratory using a simple imaging system with a DM and no coronagraph<sup>14,15</sup> and in numerous computer simulations.<sup>16</sup> In our MSWC and SNWC experiments a suppression factor of 10 was simultaneously reached both for the primary and the secondary speckles in a  $2 \times 2\lambda/D$  dark zone (DZ) in the simulated binary system. Our next goal is to demonstrate MSWC with a real coronagraphic instrument and show that MSWC can achieve at least an order of magnitude better contrast on binary stars than conventional SSWC techniques on binaries.

In this paper we present results of our MSWC experiments with an internal source of Subaru Coronagraphic Extreme Adaptive Optics System (SCEXAO) and discuss the main factors that limit the achieved MSWC performance. After brief summary of the MSWC and SNWC principles (Sections 2.1 and 2.2) we describe a Speckle Nulling based implementation of the MSWC technique (Sections 2.3). The details of a binary star simulation are discussed in Section 3.1. Sections 3.2 and 3.3 present results of the numerical simulations and experiments with the SCEXAO internal source that are compared and discussed in Section 4.

## 2. WAVEFRONT CONTROL

Any region of interest (ROI) in a binary system contains light from both binary components. Because the primary speckles and the secondary speckles are mutually incoherent, a conventional SSWC at best removes the speckles of one of the stars (primary) but not from another (secondary). To remove the secondary star light, some modification of existing wavefront control (WC) methods is necessary. Such modifications have been developed<sup>12,14,15</sup> based on various WC methods, including Electric Field Conjugation (EFC),<sup>17</sup> speckle nulling (SN),<sup>18</sup> etc. We call such algorithms as MSWC techniques.

### 2.1 Multi-Star Wavefront Control concept

We consider the main idea of MSWC using the simplest SN based approach. Any sinusoidal DM shape affects only a few localized regions in the focal plane with the rest of areas remaining practically unchanged. For example, an appropriately selected sinusoidal DM mode *PRIM\_A* produces a diffractive peak  $\mathbf{A}_p$  (Fig. 1, top) destructively interfering with the primary speckle located in a chosen focal plane location  $\mathbf{A}$ . This DM mode does not affect the secondary speckle in  $\mathbf{A}$ . However, it contaminates the focal plane in locations  $\mathbf{B}_p, \mathbf{B}_s$  such that all the vectors  $\overrightarrow{\mathbf{PB}_p}, \overrightarrow{\mathbf{SB}_s}$  are equal to  $\pm\overrightarrow{\mathbf{PA}}$ . Locations  $\mathbf{P}$  and  $\mathbf{S}$  are centers of the primary and the secondary stars respectively.

Similarly, the sinusoidal DM mode *SEC\_A* (Fig. 1, middle) produces a diffractive peak  $\mathbf{A}_s$  destructively interfering with the secondary speckle in  $\mathbf{A}$ , does not affect the primary speckle in  $\mathbf{A}$ , and contaminates the focal plane with speckles  $\mathbf{C}_p, \mathbf{C}_s$  ( $\overrightarrow{\mathbf{PC}_p}, \overrightarrow{\mathbf{SC}_s} = \pm\overrightarrow{\mathbf{SA}}$ ).

Superposition (or consequent use) of the DM modes *PRIM\_A* and *SEC\_A* (Fig. 1, bottom) would completely suppress both the primary and secondary speckles in  $\mathbf{A}$ , and contaminate the focal plane in all BC locations ( $\{\mathbf{BC}\} = \{\mathbf{B}_{p,s}\} \cup \{\mathbf{C}_{p,s}\}$ ). All three DM modes practically do not change speckles in the rest of the focal plane.

To suppress light in an extendent ROI (Fig. 1) none of the contamination speckles  $\{\mathbf{BC}_A\}_{A \in ROI}$  should hit the ROI. It is equivalent to a nonredundancy requirement, meaning that any vector  $\overrightarrow{\mathbf{PA}}_{A \in ROI}$  should be equal to none of the  $\overrightarrow{\mathbf{SA}}_{A \in ROI}$  vectors.

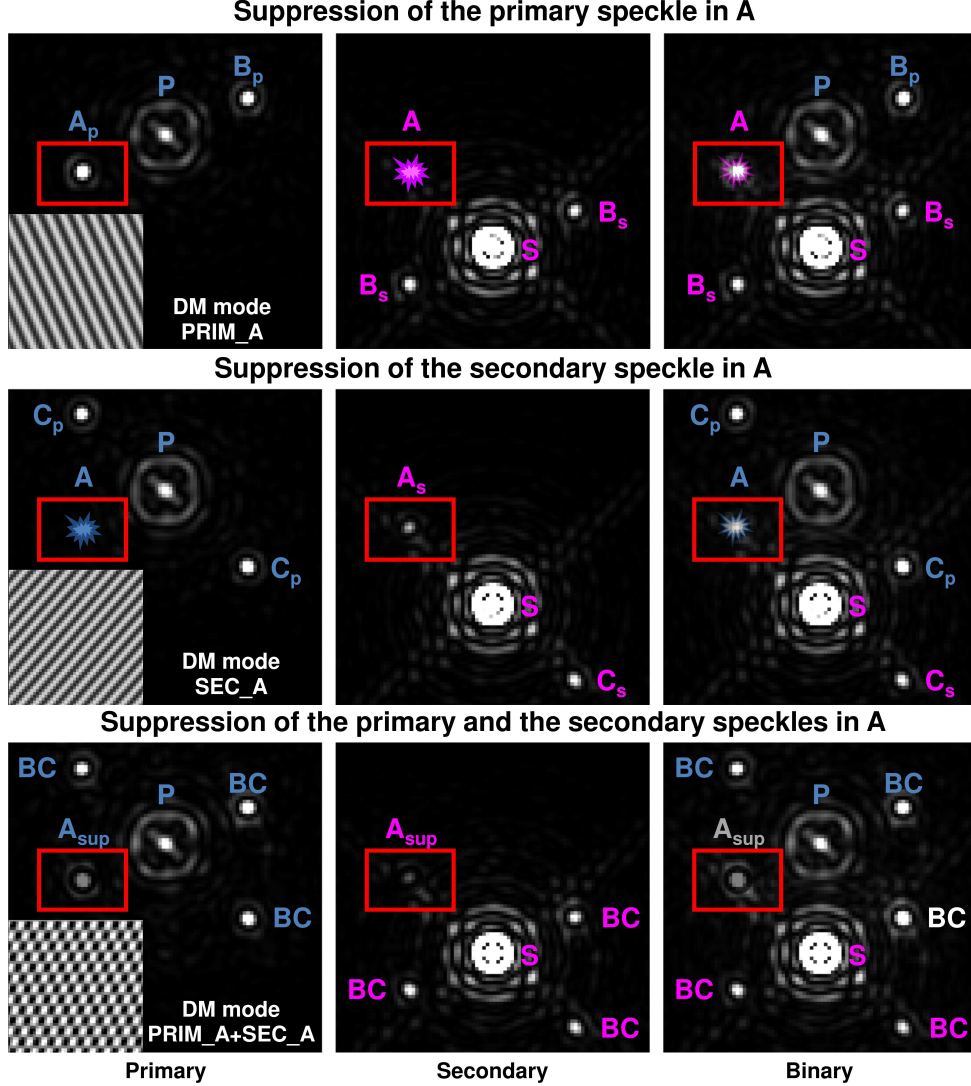


Figure 1. The Multi-Star light suppression: the primary (top), the secondary (middle) and Multi-Star (bottom) speckles corrections are presented as seen in the primary, the secondary and the binary images with the corresponding DM modes. The DM generated peaks  $A_{p,s}$  and suppressed speckles  $A_{sup}$  are shown together with the contaminating speckles  $B_{p,s}$ ,  $C_{p,s}$  and  $BC$ . The suppressed speckles are located in an extended ROI drawn as a red rectangle. The primary and secondary speckles are blue and pink respectively. Note that the primary star is blocked by the occulter.

## 2.2 Super-Nyquist Wavefront Control basics

The approach described above allows to suppress the light in the binary DZ assuming that the DM can control speckles in the ROI. However, any DM can correct the star light in the sub-Nyquist region around the star and is not able to directly control light outside of the Nyquist limit in the super-Nyquist region (Fig. 2,a). The sub-Nyquist region is not very large. For example, the Nyquist limit of the  $32 \times 32$  DM is only equal to  $16\lambda/D$ . As a result, any direct DM control cannot remove the secondary light for all the binaries with separation larger than 2 Nyquist limits (e.g. for  $\alpha$  Cen with separation varying between  $1''.2$  and  $22''$ ).

The solution of the super-Nyquist light correction is well known from an ancient radio-engineering heterodine principle (Fig. 2,a). In accordance with this principle, the pupil/DM modulation with the carrier "frequency"  $f_C$  replicates a signal at an intermediate sub-Nyquist "frequency"  $f_I$  to the super-Nyquist "frequency"  $f_S = f_C + f_I$ .

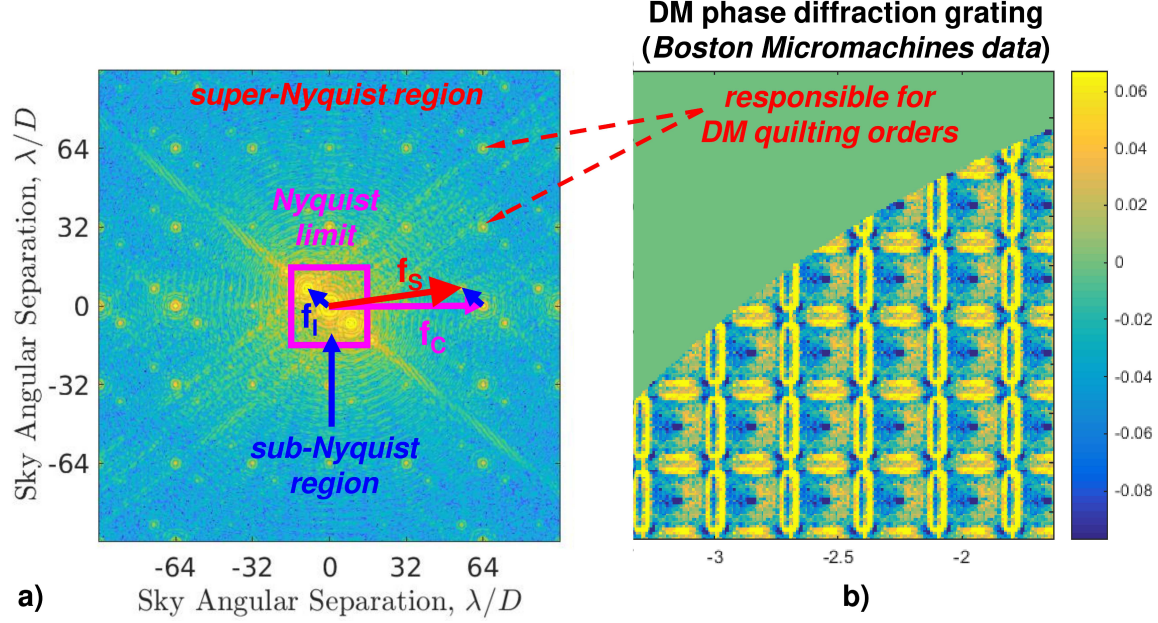


Figure 2. Light control in the super-Nyquist region, heterodine principle.

This allows to control the light in a super-Nyquist ROI by affecting the pupil plane electric field with an appropriately chosen sub-Nyquist DM control modes with frequencies  $f_{control} = f_{ROI} - f_C$ . The pupil/DM modulation with the carrier "frequency" can be performed by either a diffraction grating or any grating-like structure that is naturally presented in the pupil, e.g. by the DM "quilting" presented in some DM models,<sup>19</sup> (Fig. 2,b).

The MSWC and SNWC can be generalized by combining both in a general super-Nyquist MSWC (MSWC-s) that allows to create the binary DZ anywhere in the focal plane. What is necessary is to ensure that one of the diffraction orders from the secondary star is within the sub-Nyquist region of the primary star. For a grating that has the same period as DM actuators there will be always one diffraction order within a sub-Nyquist distance to any point in the focal plane, so a dark zone can be created anywhere. A key requirement, however, is that the intensity of the diffraction order needs to be greater (by at least by a factor of 100 as known from radio-engineering applications) than the intensity of the secondary speckles in the ROI. Small intensity of the diffraction orders leads to DM solutions with high DM strokes and low Strehl ratio of the focal plane images.

### 2.3 Speckle Nulling based implementation

In practice it is impossible to completely decouple DM modes responsible for the primary and the secondary speckles suppression – any DM mode always affects both binary components to some level. In a long WC run this second order effect is not negligible. The WC that completely suppresses the primary speckles and then switches to the secondary speckles correction does not work. The secondary speckles correction would destroy the earlier created primary DZ. One way to solve this problem is to alternate the primary and secondary speckle correction, e.g. suppress the primary speckles in odd and the secondary speckles in even WC iterations. We implemented this approach based on the SN procedure routinely used at the Ames Coronagraph Experiment (ACE) laboratory since 2010. We choose SN based MSWC because it is simple, does not require an accurate optical system model, and is less sensitive to the instrumental drifts/instabilities expected for the ground based coronagraphic systems.

The program code was originally developed to remotely run WC on the HCIT testbed at JPL. In the chosen software architecture, independently running communication server (see Section 3.3) is responsible for the data exchange between the hardware independent WC code with a remote imaging system. In each iteration the WC

code performs three main steps: (1) inloop calibrations/realignments, (2) probing, and (3) correction/suppression of the selected DZ speckles. The algorithm does not use any model dependent system knowledge. It only relies on parameters that can be measured directly during inloop calibrations. These calibrations include a photometric calibration and geometrical calibrations. Realignment procedures are described in Section 3.3. Photometric calibration generates a diffraction peak of known contrast in the DZ, that is used to calibrate the DZ contrast. Geometrical calibrations are discussed below.

The relationship between the spatial frequency  $(f_x, f_y)$  of a sinusoidal DM mode and the location  $(x, y)$  of the corresponding focal plane speckle is given by the equation

$$(f_x, f_y) = \begin{pmatrix} g_{xx} & g_{xy} \\ g_{yx} & g_{yy} \end{pmatrix} \begin{pmatrix} x - x_c \\ y - y_c \end{pmatrix} \quad (1)$$

where  $(x_c, y_c) = (x_p, y_p)$  suppresses the primary speckles, and  $(x_c, y_c) = (x_s, y_s)$  should be used to correct the secondary speckles. The geometrical transformation matrix  $(g_{\alpha\beta})$ , the primary star center  $(x_p, y_p)$  and the secondary star center  $(x_s, y_s)$  are measured by the geometrical calibration procedures. Alternating correction of the primary and secondary speckles is equivalent to alternation between  $(x_p, y_p)$  and  $(x_s, y_s)$  in Eq. 1. It can be easily done in the original single star SN.

Our probing step uses sinusoidal DM probes that are standard for SN. In each iteration the set of DM probes  $\{probe_k(x_{DM}, y_{DM})\}_{k=1}^K$  can be written as

$$probe_k(x_{DM}, y_{DM}) = probe\_amplitude \times \sum_{i=1}^N \sin(x_{DM}f_x^i + y_{DM}f_y^i + 2\pi k/K + \varphi_i), \quad (2)$$

where  $(x_{DM}, y_{DM})$  are coordinates in the DM plane,  $(f_x^i, f_y^i)$  is the DM sinewave frequency that produces a diffractive peak in the location of i-th speckle, k is the probe number,  $\varphi_i$  is a random phase uniformly distributed over the interval  $[0, 2\pi)$ , and  $K \geq 3$ . Such probing functions provide simultaneous estimation of the electric field phase  $\Phi_i$  for each correcting DZ speckle assuming that selected speckles are independent. The amplitude of the probing functions and number of corrected speckles  $N$  are stored in a configuration file together with other parameters such as the DZ geometry, amplitude and position of the calibration peaks, etc. All these parameters can be tuned/changed without interruption of the WC run.

Finally, the DM correction map can be presented as

$$DM\_correction(x_{DM}, y_{DM}) = \sum_{i=1}^N correction\_amplitude_i \times \sin(x_{DM}f_x^i + y_{DM}f_y^i + \Phi_i), \quad (3)$$

where  $correction\_amplitude_i$  value that suppresses the i-th speckle can be found by using an amplitude scanning procedure. In this procedure all the amplitudes are initially set equal to  $probe\_amplitude$ . In each scanning step all i-th amplitudes that increase unprobed intensity of the i-th speckles are reduced. The scanning is continued until all correcting speckles will be suppressed or the correction amplitudes become negligible.

Another way to implement MSWC is to solve a few wavefront control problems simultaneously with one DM. Some algorithms, such as EFC, already lend themselves naturally to solving simultaneous wavefront control problems. For example, EFC solves the problem of broadband light suppression by simultaneously solving several narrowband EFC problems.<sup>17</sup> In the same way EFC like algorithms generalize to MSWC for two or more stars.

### 3. SCEXAO DEMONSTRATION

The described sub-Nyquist MSWC concept was tested in our several experiments with the SCEXAO instrument by using an internal SCEXAO calibration source to simulate a real sky binary system. In these MSWC experiments we planned to demonstrate at least  $10\times$  improvement in the monochromatic contrast relative to a control experiment running a standard SSWC on the simulated binary.

The SCEXAO is a high-contrast instrument and testbed installed at the Nasmyth platform of the Subaru Telescope (Fig. 3). It is designed for a dual purpose:<sup>20</sup> perform on-sky observations of exoplanets, debris disks



Figure 3. SExAO on the infrared Nasmyth platform of the Subaru Telescope.

and other targets requiring high-angular resolution and high-contrast, and test innovative technologies necessary for future high-contrast imagers. As a testbed, SExAO can simulate a large variety of scenarios, for both ground and space applications. At the telescope, SExAO sits behind the facility adaptive optics AO188, which provides a first level of wavefront correction. SExAO performs the second level of correction, using a combination of a visible pyramid wavefront sensor, and a 2000-actuator MEMs deformable mirror. After the DM, the light is split between visible (600-950nm) and infrared (950-2400nm) and distributed to various modules. The infrared path is equipped with a variety of coronagraphs (Lyot, vector vortex, 8-octant phase mask, phase-induced amplitude apodization complex mask coronagraph, vector apodized phase mask). Science images can be taken with different detectors: the integral field spectrograph CHARIS, the MKIDS Exoplanet Camera (MEC), or other fast NIR cameras (First Light Imaging C-RED ONE and C-RED 2 cameras). The instrument was designed to allow full remote control from anywhere in the world, which makes it a great asset for experiments like this, especially when lockdowns were in place in 2020.

### 3.1 The simulated target and the dark zone geometry

To select our target, we searched for a binary star where the secondary component would have a significant amount of leak and be the main source of noise after SSWC was applied.

Assuming that the contrast floor of SExAO is about  $10^{-6}$  and the residual speckles after SSWC are dominated by uncorrectable secondary speckles, the minimal initial contrast of the secondary that provides the required suppression level of the secondary speckles should be larger than  $10^{-5}$ . In our experiments we simulated a binary star STF3121 AB (HIP 45617). This star satisfies three main requirements: (1) speckles from both stars are correctible with a direct DM control; (2) the components are far enough to create at least  $2 \times 2 \lambda/D$  dark zone; (3) in the region of interest the initial contrast both the primary and the secondary speckles is about the same and approximately equal to  $5 \times 10^{-5}$ .

STF 3121 AB is a close K0 visual binary ( $\pi = 0''.058$ ) with the orbital period of 34.17 years<sup>21</sup> and large semi-axis  $a=0''.68$ . The system separation  $\rho$  varies between  $0''.2$  and  $0''.8$ .<sup>22</sup> The magnitude difference  $\Delta m$  between the components is equal to 0.79 that corresponds to the components brightness ratio of 0.48. The system is

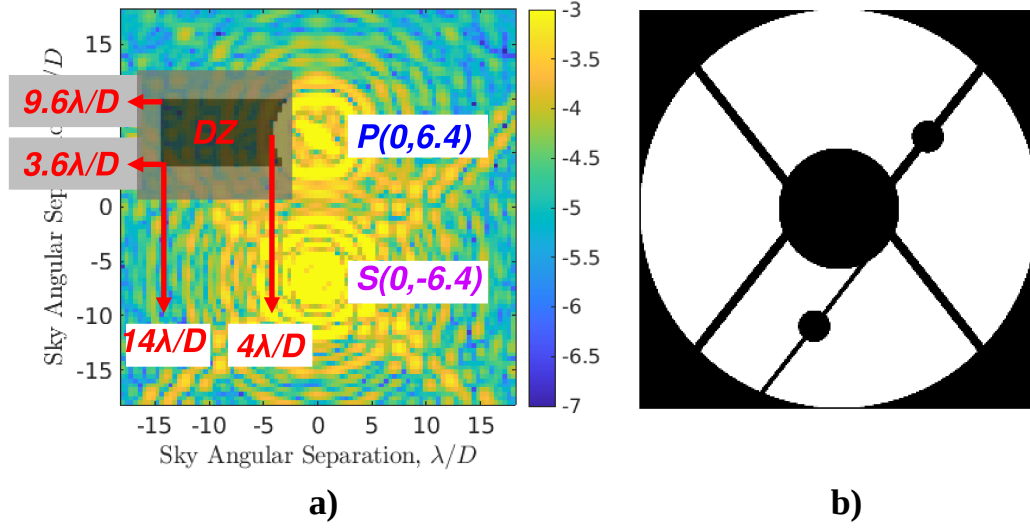


Figure 4. The binary and DZ geometries (a) and the Subaru pupil (b).

variable with the variability caused by rotation of large surface spots, like Sun spots, and chromosphere activity of components. This binary is also a part of a quadruple system. It is accessible by SCEXAO.

We simulated STF 3121 AB with the separation of  $0''.518$  corresponding to 32 px distance between the components in the focal plane of the coronagraph. The system geometry with the vertically offset components is shown in Fig. 4. The primary star is blocked with the  $2.8 \lambda/D$  occulter. The core of the secondary star is not blocked. To get a double star image we take separate images both the primary and secondary components for two different positions of the internal source, normalize the secondary image and superimpose both images. The used dark zone geometry is also shown in Fig. 4. Three edges of the dark zone are sides of  $12 \times 6 \lambda/D$  rectangle centered relative to the primary star at  $8 \lambda/D$  along the horizontal axis and aligned with the primary center in the vertical direction. It sets the Outer Working Angle (OWA) equal to  $14 \lambda/D$ .

The remaining DZ edge is a circular arc with the radius of  $4 \lambda/D$  (Inner Working Angle, IWA) with the center that matches the primary star location. For such a dark zone all the DM modes used to correct the primary and secondary speckles are non-redundant in the sense discussed in Section 2.2.

### 3.2 Numerical simulations

We estimated the expected method performance through numerical simulations. The SCEXAO instrument is modeled as a simple, compact Lyot-style coronagraph system with key planes included and matching physical SCEXAO parameters for the multi-star wavefront control configuration expected during the experimental tests. The planes included in the model are (1) telescope pupil conjugate (Fig. 4), (2) occulter focal plane, (3) Lyot

Table 1. Summary of SCEXAO model parameters

| Parameter                | Value                   |
|--------------------------|-------------------------|
| Wavelength, $\lambda$    | 1550 nm                 |
| Camera Sampling          | 2.5 Pix per $\lambda/D$ |
| Focal Plane IWA,         | $2.8 \lambda/D$         |
| Lyot Stop Outer Fraction | 0.95                    |
| Lyot Stop Inner Fraction | 0.40                    |
| Wavefront Aberrations    | $\lambda/20$ RMS        |

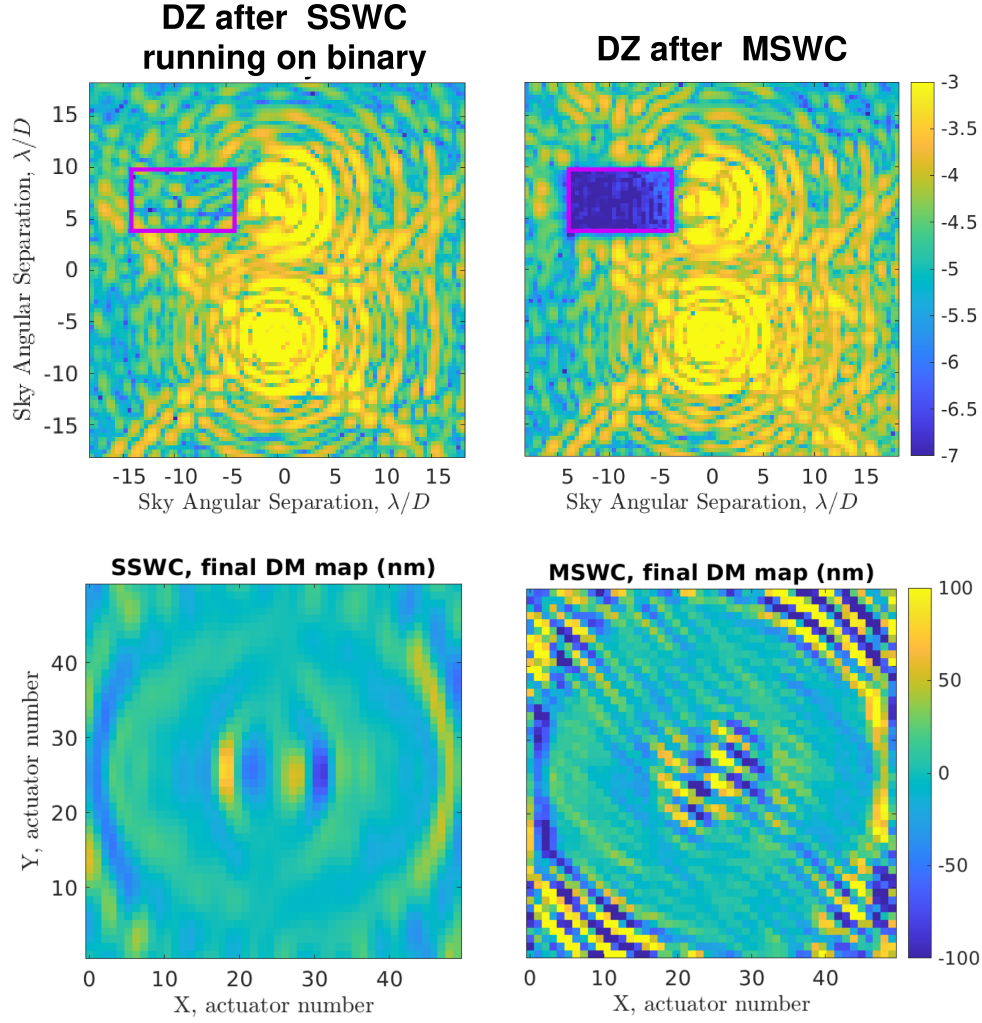


Figure 5. Simulation of MSWC on SCEExAO. The binary dark zones (top, highlighted with rectangles) created in SSWC run with contrast of  $3.2 \times 10^{-5}$  (left) and in MSWC run with contrast of  $2.6 \times 10^{-7}$  (right). Corresponding DM maps are shown in bottom.

plane, and (4) science camera. These optical planes are related to each other by Fraunhofer propagations. The optical model implements propagation from the conjugate pupil plane to the Lyot plane through a convolution operation applying the effect of the focal plane mask. The set of system parameters is listed in Table 1. The 2K Boston MEMS DM is conjugate to a pupil mask prior to the focal plane occulter. The pupil mask consists of a replica of the Subaru pupil with additional masking for defective actuators on the DM. A circular focal plane mask with a  $2.8 \lambda/D$  inner working angle is used for these experiments, set to block the primary component with the secondary component unblocked. The Lyot stop consists of a composite mask that includes the thickened Subaru pupil and an annular Lyot stop with an inner fraction of 0.4 and an outer fraction of 0.95. At the science camera, there are 2.5 samples per  $\lambda/D$ , which corresponds to the real SCEExAO plate scale. All simulations were performed for monochromatic PSFs at the central wavelength of 1550 nm (H-band wavelength). The strength of the aberrations was chosen to reproduce the initial DZ contrast expected in a real experiment.

With the initial dark zone contrast of  $8.6 \times 10^{-5}$  and the contrast floor of about  $3.2 \times 10^{-5}$  the SSWC reaches the  $3.3 \times 10^{-5}$  contrast after 90 iterations (Table 2, Fig. 5, Fig. 7). At the same time, it takes about 190 iterations to reach  $3.2 \times 10^{-6}$  contrast with SN based MSWC. In a full run MSWC reaches contrast of 2.6

## The experiment optical layout (SCExAO IR bench, Lyot mode)

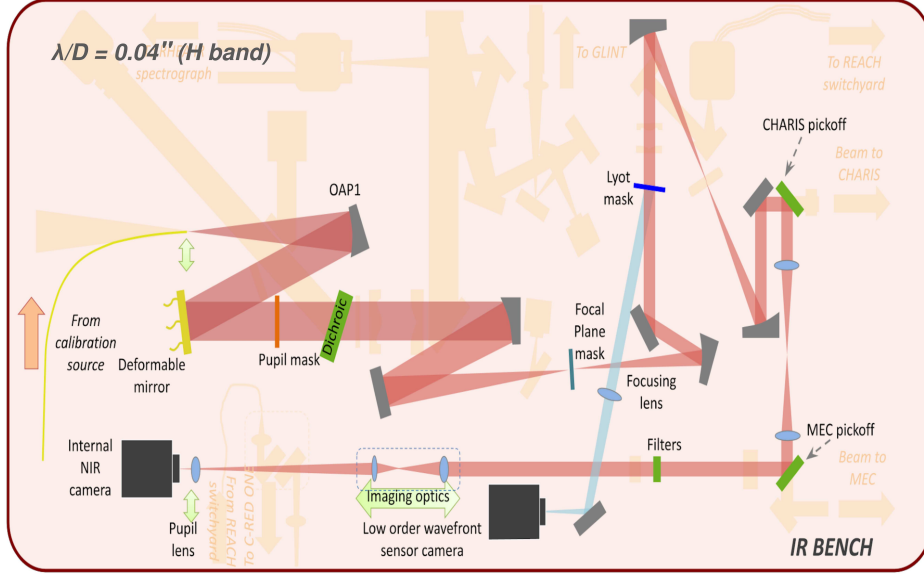


Figure 6. The SCExAO infrared bench in Lyot configuration.

$\times 10^{-7}$ , corresponding to the improvement of about 120 times in comparison with the SSWC contrast. This implies that in the ideal case our goal should be easily achievable unless some unmodeled limiting factors affect the coronagraph performance.

### 3.3 SCExAO experiments

For the MSWC runs, only the infrared SCExAO bench was used (Fig. 6). In the Lyot configuration a supercontinuum source simulating starlight is injected in a photonic crystal fiber. A series of filter wheels allows tuning the flux with different neutral densities. The output of this fiber can be placed anywhere in the focal plane at the entrance of SCExAO, thanks to a X/Y motorized mount. Since we only have one fiber in the focal plane, we simulate a binary system by dithering the fiber between images. The light is then collimated on the DM, then goes through a pupil mask simulating the pupil of the Subaru telescope (Fig. 4,b). The light is then focused again in a plane where the focal plane mask of the coronagraph is placed. For this experiment, we only used the Lyot coronagraph with an inner working angle of 113 mas on-sky ( $2.8\lambda/D$  at 1550 nm). The light is collimated again onto the pupil plane Lyot mask. A low-order wavefront sensor can use the light reflected by the Lyot mask to correct for low-order aberrations, but was not necessary for this experiment. Finally, the light goes through a filter wheel, and is reimaged on the First Light C-RED 2 camera. The filter used was a narrowband filter around 1550 nm, with a bandwidth of 25 nm. The C-RED 2 camera was used in a windowed mode of 128x128 pixels, at 100 Hz (although it can run at several kHz in this mode).

The wavefront control calculations were done remotely at NASA Ames (Section 2.3). The wavefront control code sends DM commands as FITS files (2D or cubes) on a local SCExAO computer using a SCP protocol. The commands are then physically sent to the DM, and the resulting images are then recorded with the C-RED 2 camera and saved also as FITS files. The user then copies the images back to the remote computer for analysis. This communication scheme is simple and convenient compared to direct hardware access, but is quite slow. It could take up to 20-30 sec to get an image/image cube, resulting in the WC run rate of 10-15 min/iteration, and a run taking hours or even days. At that timescale, drifts of the PSF and the occulter on the detector can appear (Section 4). Without compensation, these drifts up to several  $\lambda/D$  upstream of the coronagraph interfere with the creation of dark zones. For this reason, we developed an automatic alignment procedure that can be

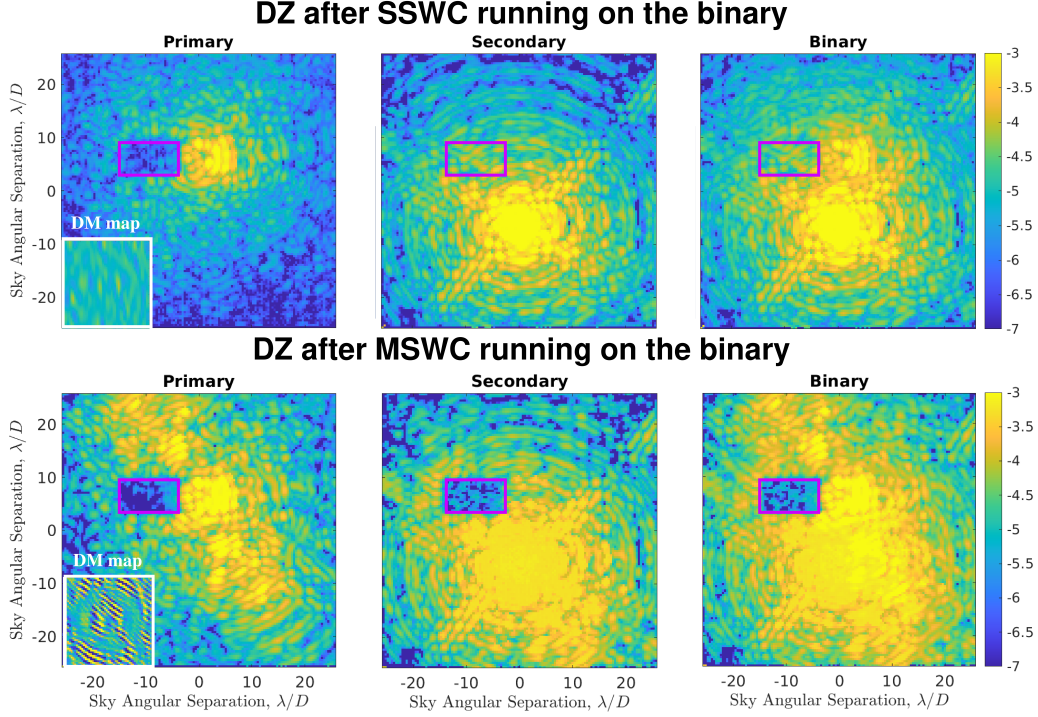


Figure 7. The primary, secondary and binary dark zones (highlighted with rectangles) created in SSWC run and in MSWC run at SCEXAO. Corresponding DM maps are shown in bottom left corners of the primary images. Dark zones contrasts are collected in Table 2.

started from the WC code. During this procedure, the coronagraph is moved out of the way, the source is set to avoid saturation on the detector, and the PSF is recentered using a combination of the motorized DM stage and tip/tilt modes on the DM itself, to remove any drifts from the DM stage. This recentering has a precision of about  $0.05 \lambda/D$ . After the PSF is recentered, the coronagraph is put back in place for the main star, then realigned automatically by iteratively scanning the position of the focal plane mask in X and Y, measuring the total flux and fitting a parabola to the resulting flux variations. The coronagraph is centered once the total flux is minimal in the image. This procedure resulted in the alignment of the focal plane mask at better than  $0.1 \lambda/D$ . The alignment procedure was proven to be quite robust over a few days of testing, with minimal intervention from the instrument operator.

A total of twelve independent wavefront control experiments were carried out. Last three of these runs were successful. Here we present only results of the final SCEXAO run that includes both MSWC and control SSWC tests running on the binary , reliable contrast calibrations and showing more than tenfold MSWC performance improvement with respect to the corresponding control SSWC run. The created dark zones are presented in

Table 2. Simulated and experimental performance of MSWC with SCEXAO

|                           | DZ,<br>[ $\lambda/D$ ] | IWA,<br>[ $\lambda/D$ ] | OWA,<br>[ $\lambda/D$ ] | Contrast [ $\times 10^{-5}$ ], simulated/experimental |            |            |
|---------------------------|------------------------|-------------------------|-------------------------|-------------------------------------------------------|------------|------------|
|                           |                        |                         |                         | primary                                               | secondary  | binary     |
| initial                   |                        |                         |                         | 5.6/4.2                                               | 3.0/4.6    | 8.6/9.2    |
| SSWC                      |                        |                         |                         | 0.030//0.15                                           | 3.2/5.2    | 3.2/5.4    |
| MSWC                      |                        |                         |                         | 0.015/0.16                                            | 0.011/0.25 | 0.027/0.41 |
| improvement,<br>SSWC/MSWC |                        |                         |                         | 2.0/0.93                                              | 290.9/20.8 | 118.5/13.2 |

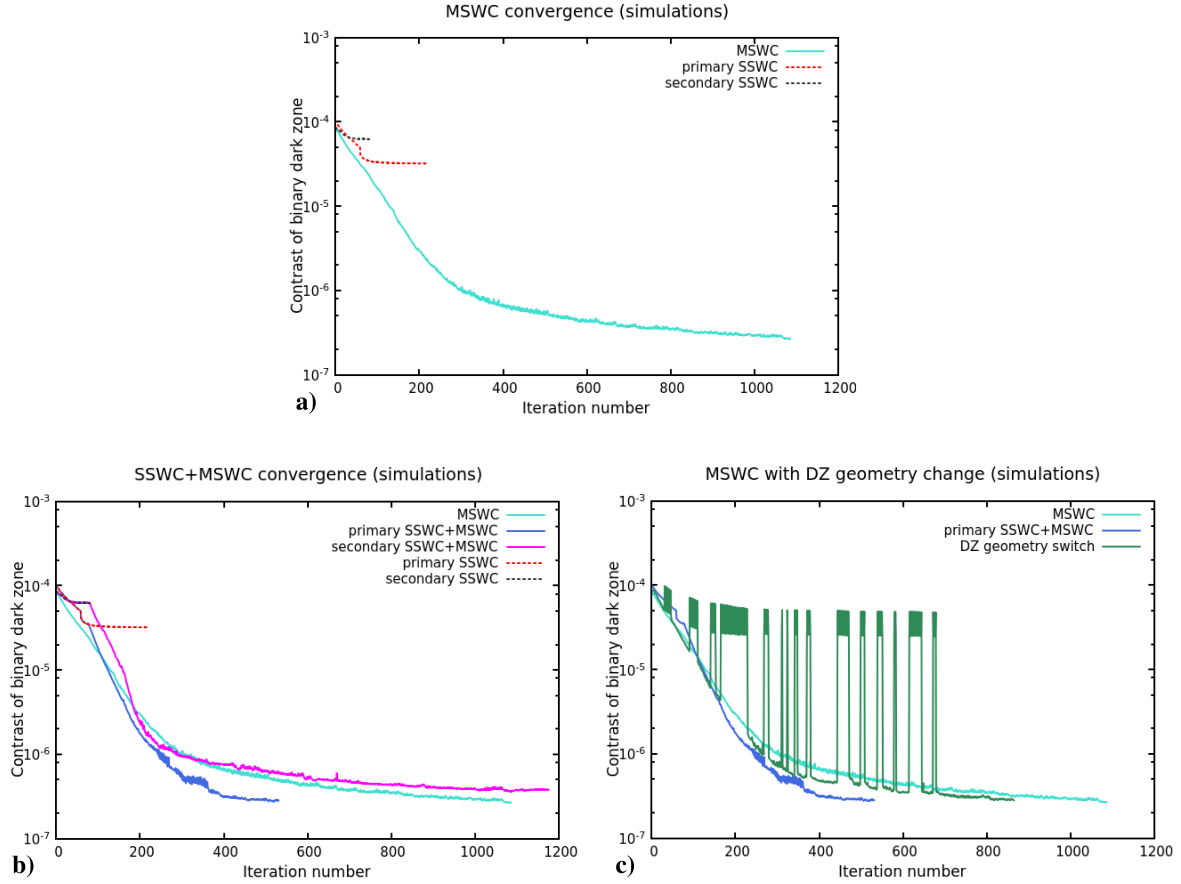


Figure 8. MSWC convergence (numerical simulations): a) pure MSWC; b) "SSWC+MSWC" algorithm; c) MSWC with DZ geometry change.

Fig. 7. Top row contains images of the binary components and the binary itself after the control SSWC run. It took only 33 iterations (Fig. 8,a) for SSWC to suppress the primary speckles to the contrast of  $1.5 \times 10^{-6}$  and reach the SSWC contrast floor of  $5.4 \times 10^{-5}$ . The final SSWC binary contrast is mainly limited by the secondary speckles. MSWC shows much better performance. The contrast of  $4.1 \times 10^{-6}$  is reached in the MSWC run (bottom row) that is by a factor of 13.2 better than the contrast floor reached in the control SSWC run (Table 2, Fig. 10).

#### 4. DISCUSSION

In our SCEExAO experiments we demonstrated that MSWC achieves an order of magnitude better contrast on a binary target than standard single-star wavefront control. However, the real performance of the MSWC with SCEExAO is by a factor of 10-20 worse than the simulated performance. We consider the following factors that reduce the experimental MSWC performance:

1. The single-star performance of SCEExAO is limited. The contrast floor with the SCEExAO configuration identical to our setup is about  $10^{-6}$  [23].
2. Slow loop rate and convergence speed of applied algorithms.
3. The SCEExAO instrumental drift combined with slow algorithm convergence can significantly reduce performance.

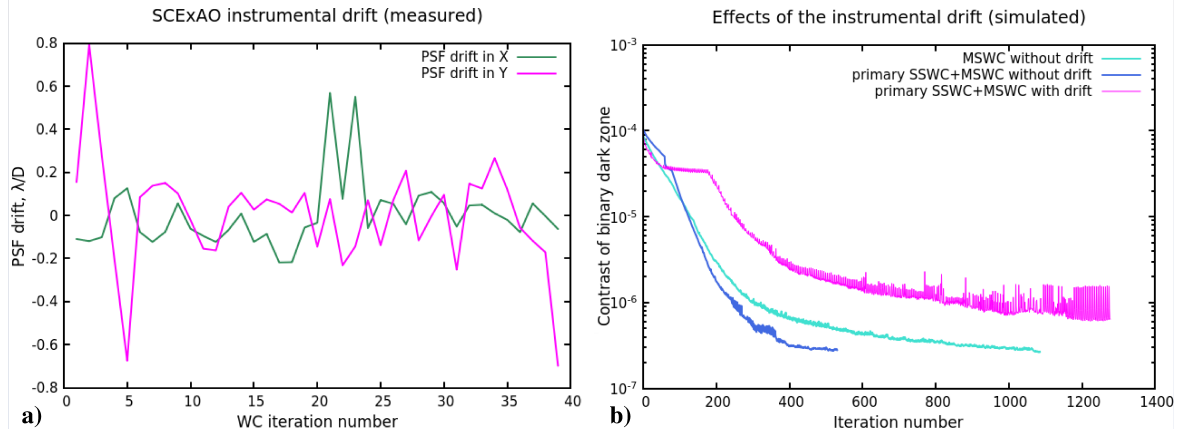


Figure 9. Effect of the SCEXAO instrumental drift on the MSWC performance: a) measured PSF drift; b) simulated "primary SSWC+MSWC" algorithm performance with the instrument that shows PSF drift. The measured sequence of the PSF centers was periodically continued to simulate the PSF drift in a longer simulation run.

4. Photometric errors. We expect that imperfect the camera dark correction can approximately bias our contrast estimates by  $1 \times 10^{-6}$ .

Reasonable duration of a real WC run should not exceed 200-300 iterations. The SN based MSWC is very robust to model errors, but is slow. It takes about 300 iterations to reach about  $10^{-6}$  contrast even in simulations (Fig. 8,a). Any instability of the real instrument would slow down the convergence speed. To improve the algorithm convergence the following methods can be used:

- a) changing the number of corrected speckles during the WC run;
- b) the WC run can be started with the SSWC that corrects primary or secondary speckles first and switch to the MSWC after the SSWC reaches its contrast floor ("SSWC+MSWC" algorithm);
- c) switching between different DZ geometries inside of the run.

The approach that corrects the primary speckles first shows the best convergence speed (Fig. 8,b). However, in our final experiment we choose to correct the secondary speckles first because it affects the Shtrehl ratio less.

Switching of the DZ geometry (Fig. 8,c) shows slightly worse performance than the "SSWC+MSWC" algorithm. However, it is very efficient if the WC convergence is slowed down by bright speckles near the DZ boundary. In the presented plot three contrast levels can be identified by contrast jumps on the chart. The deeper contrast level corresponds to the main DZ geometry that matches the desired ROI. Two shallower levels correspond to two different DZ shapes applied to the primary and secondary speckles correction in iterations with changed DZ geometry. In a real run, any combination of all these methods can be used.

To estimate how the instrumental drift affects the MSWC performance we measured the PSF drift with respect to the camera during one of MSWS runs (Fig. 9,a). The measured data were included in our numerical simulations (Fig. 9,b). Although the achieved contrast floor is about  $6 - 7 \times 10^{-7}$ , the simulations indicate that with the measured PSF drift it is difficult to get the binary DZ contrast better than  $10^{-6}$ . The occulter drift also needs to be considered. Taken into account both the PSF and occulter drifts can easily make the goal of our experiment unreachable unless they are compensated. We could not get the MSWC improvement factor better than 3-5 in our early experiments until we implemented the inloop alignment procedures (Section 3.3).

Finally, in Fig. 10 we show how the binary DZ contrast changed with iteration number in the real SCEXAO run. The presented plot confirms that MSWC can achieve at least tenfold increase in the binary DZ contrast in comparison with conventional SSWC methods applied to binary systems.

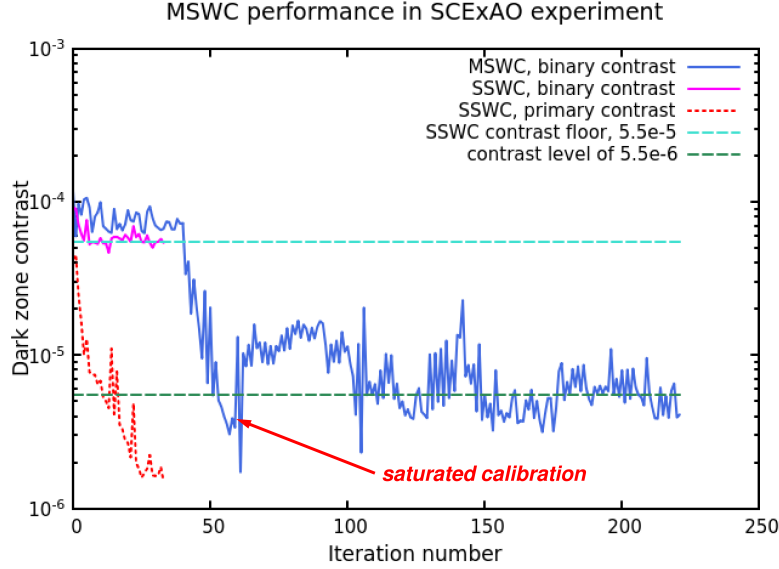


Figure 10. Experimental performance of the MSWC with SCEXAO: the binary DZ contrast vs iteration number is presented for the MSWC run and the control SSWC run. The primary contrast change in the SSWC run is also shown. The SSWC contrast floor of  $5.5 \times 10^{-5}$  and the desired MSWC contrast performance ( $5.5 \times 10^{-6}$ ) are marked with dashed lines.

## 5. SUMMARY

MSWC is a wavefront control technique that allows exoplanet imaging in binary star systems. In this paper we presented results of our sub-Nyquist Multi-Star Wavefront Control experiments with the SCEXAO instrument that simulated a real sky binary STF3121 AB with an internal instrument source. This is the first MSWC demonstration with a commissioned coronagraph. The goal of these experiments was to show that MSWC can achieve tenfold increase in the contrast on binary stars in comparison with conventional SSWC methods applied to binaries.

In our SCEXAO test the narrow-band contrast of  $4.1 \times 10^{-6}$  has been reached in a  $12 \times 6$  DZ, separated from the primary component by  $4\lambda/D$ . This is by a factor 13.2 better than the contrast  $5.2 \times 10^{-6}$  reached in the control SSWC run. We identified the PSF and occulter drifts caused by the instrument instability as the main factors limiting the MSWC performance with SCEXAO.

Finally, we confirmed that the developed WC method can be implemented on existing science instruments, like SCEXAO, without major modifications of this instruments. Particularly, sub-Nyquist MSWC need no instrumental modification at all.

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