

First Generation Parabolic Deformable Mirror for the ExoSpec Project

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ABSTRACT

The Exoplanet Spectroscopy (ExoSpec) project links four different tasks at Goddard Space Flight Center (GSFC) to facilitate efficient imaging and characterization of exoplanets. One of the tasks is the development of parabolic deformable mirrors to improve on the current state-of-the-art wavefront sensing and control implementations that are baselined to have two high-actuator count flat deformable mirrors (DMs). The current baseline has two DMs at a considerable separation distance to effectively control both amplitude and phase aberrations. This significant separation poses packaging challenges to the direct imaging missions. We can mitigate this issue by making the off-axis imaging elements in the optical train controllable. Besides addressing the packaging challenges, this technique reduces the risk of having the entire coronagraph instrument's performance depend on two high-actuator count DMs. Simulations show that making imaging elements deformable increases the overall controllable bandwidth - it would be possible to control wavefront aberrations up to 35% bandwidth over a 5 - 12 $\frac{\lambda}{D}$. GSFC has worked with a commercial vendor to produce a first-generation parabolic DM and built a testbed in an environmentally controlled cleanroom to experimentally demonstrate the use of a parabolic DM in a coronagraph instrument. This versatile testbed is designed to test different DM architectures and various low-order wavefront schemes. This provides us with a basis for comparison with different DM configurations —1) flat DM, 2) parabolic DMs, and 3) flat DM and parabolic DMs. In this paper, we will provide an update on our parabolic DM work.

1. INTRODUCTION

The objectives of future flagship space missions focused on UV/Optical/Infrared exploration of exoplanet atmospheres will lead to demanding design criteria for instrument wavefront control, spatial and spectral sampling, spectral range, and detector capabilities. The ExoSpec Project represents a consolidation of four separate research endeavors conducted at Goddard, aimed at facilitating and improving the spectral analysis of exoplanets observed through direct imaging. The work presented in this communication pertains to technology related to wavefront control. For detailed information about the ExoSpec project, we refer readers to Zimmerman et al.¹²

Conventional dark zone (DZ) digging (wavefront control) techniques for direct imaging of exoplanets use two high actuator count flat DMs in the optical path and algorithms such as speckle nulling,² electric field conjugation (EFC),⁴ and stroke minimization⁸ to calculate DM actuation that produces the desired high contrast dark zones. There are multiple issues associated with using two high actuator flat DMs for space missions – 1) risk of having single point failure, 2) large distance required between the DMs to effectively dig the dark zones for mission concepts such as LUVOIR that cause packaging issues with the existing rocket fairings, and 3) limited controllable bandwidth. Groff et al.⁵ showed that the parabolic mirrors used in the optical train could be made deformable with fewer actuator counts than the flat DMs to reduce the risk of a space-based coronagraphic instrument by building redundancy into the DM control. This would also increase throughput by reducing the number of optical surfaces. We have shown in our previous work that by placing the control surfaces on the sources of aberrations themselves, it is possible to increase the control bandwidth too.¹⁰ In simulation, we were able to control wavefront aberrations up to 35% bandwidth over a 5 - 12 $\frac{\lambda}{D}$ double-sided dark hole, where λ is the wavelength and D is the pupil diameter. Simulations show that low-actuator count parabolic mirrors augmented with a high-actuator density mirror at the pupil plane can create symmetric dark holes with identical contrast

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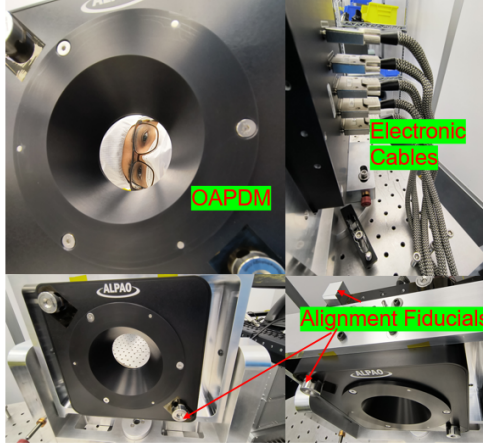


FIGURE 1: Pictures of the first-generation (Gen 1) device. Description in clockwise direction: the primary author visually inspecting the parabolic DM (OAP DM), cables connecting the DM to the control electronics, the alignment fiducials attached to the housing of the OAP DM, and the front surface of the OAP DM with the vendor logo.

values as compared to existing techniques that have two high-actuator density flat DMs. We have partnered with ALPAO (Grenoble, France), an adaptive optics company, to manufacture an off-axis parabolic DM (referred to as OAPDM and PDM). We have received a first-generation device from ALPAO and are currently characterizing it. Concurrently, we are also building a high-contrast testbed to verify the DM. The testbed is designed to be a multipurpose lab to experimentally verify different low and high-order wavefront control algorithms. In this paper, we will report the results from the ongoing DM characterization tests and the testbed under construction.

We will start Section 2 by describing the specifications of the parabolic DM, the iterative fabrication process, and the performance of the delivered device. Section 3 presents the planned layout of the lab. In this section, we will describe the functions of the two testbeds we have and present the different elements of the high-contrast imaging testbed. We will briefly discuss the alignment procedure of the testbed in Section 3 and then we conclude the paper in Section 4.

2. PARABOLIC DM

We worked with a vendor, ALPAO, to manufacture a first-generation OAPDM device, and the device was delivered in May 2023. The delivered device has the following specifications:

- Actuator pitch: 3.125 mm
- Actuators: 277
- Effective focal length: 1524 mm
- Offset distance from center of parabola: 254 mm
- Resonant frequency: 700 Hz
- Minimum frequency at phase lag of 45° : 300Hz
- Maximum settling time (at $\pm 10\%$): 0.55 ms
- Hysteresis: $< 10\%$
- Operating temperature: $25^\circ \pm 5^\circ$ C
- Functional temperature: -5°C to 45° C
- OAP shape accuracy < 23 nm rms.

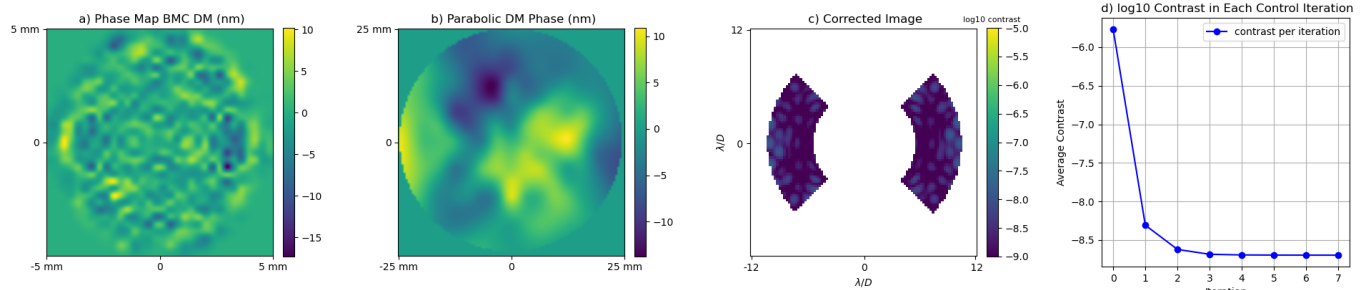


FIGURE 2: Wavefront control using the ALPAO OAP DM with a non-functional actuator. From left to right: wavefront map of the flat DM, the wavefront map of the OAP DM, corrected two-sided DZ, and contrast level in $\log_{10}$ scale at each control iteration.

The OAP DM device fabrication was an iterative process. The first prototype validated the curved membrane concept and that the OAP could be controlled. However, the DM had significant stability issues due to a complex thermo-mechanical interface - we observed a membrane drift on the order of 50 waves RMS within minutes of operation. After a thermo-mechanical redesign of the membrane, ALPAO was able to resolve the membrane stability issue and fabricate a Gen 1 device. One of the prototype devices was tested to verify that it could be transported without any damage to the device.

2.1 Device Performance

Once we received the device, we placed it on a purpose-built characterization testbed (Fig. 1 and Fig. 4) to verify that it meets the specifications. The characterization testbed is described in more detail in Section 3. During visual inspection, it was found that a single actuator was stuck in a maximally pulled position with limited control range. We simulated closed-loop control using OAPDM with a single free-floating actuator in the corresponding position to determine the acceptability of the delivered device. The simulations show that we could achieve the same level of contrast (Fig. 2) over 10% bandwidth as achieved by using the nominal device, with a small stroke penalty at surrounding actuator locations. For these simulations, we used an apodizer (Fig. 6 b) designed for a segmented pupil, a 32×32 flat DM in the pupil plane, the ALPAO OAP DM, and used the measured ALPAO influence function and wavefront residuals after flattening. Based on the simulation results, we elected to physically remove the stuck actuator. After the successful removal of the actuator, we measured the influence function of the DM, applied the DM offset commands provided by the vendor, and calculated the DM voltage to drive the surface close to the nominal parabolic surface i.e., flatten the DM. We were able to flatten the DM to 29 nm RMS from the starting wavefront of 2 microns as depicted in Fig. 5. The device still has actuator drift issues and we are actively exploring solutions for the Gen 1 device operation. We are also in communication with the vendor to change the DM fabrication material to rectify this problem for a Gen 2 device.

3. EXOSPEC TESTBEDS

The ExoSpec lab at NASA GSFC has two optical tables as shown in Fig. 3a. In this section, we will describe the design and functions of each testbed.

3.1 Characterization Testbed

The characterization table shown in Fig. 4 is designed to verify the specifications of the optical elements to be used in the verification testbed. A Zygo interferometer with a 4-inch collimated beam with center wavelength of 633 nm is used as a source. A CaliBall sphere placed in an XYZ stage is used to return the beam for double-pass interferometry. The alignment procedure involves a series of systematic steps. Initially, the Zygo interferometer in combination with a CaliBall is utilized to align a stationary OAP. This established alignment of the OAP then serves as the baseline for the subsequent alignment of the Shack-Hartmann Wavefront Sensor (SHWFS). Following this, the static OAP is substituted with the OAPDM. Once the alignment is validated, the SHWFS is

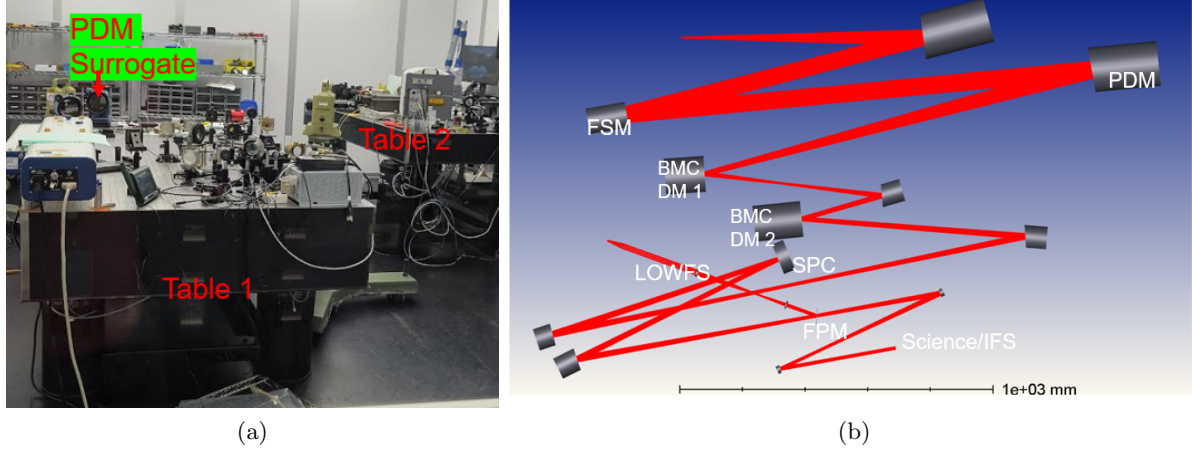


FIGURE 3: ExoSpec lab at NASA GSFC. a) The lab setup has two tables one for OAP DM verification (Table 1) and another for the characterization of optical elements (Table 2). b) Zemax model of the verification testbed.

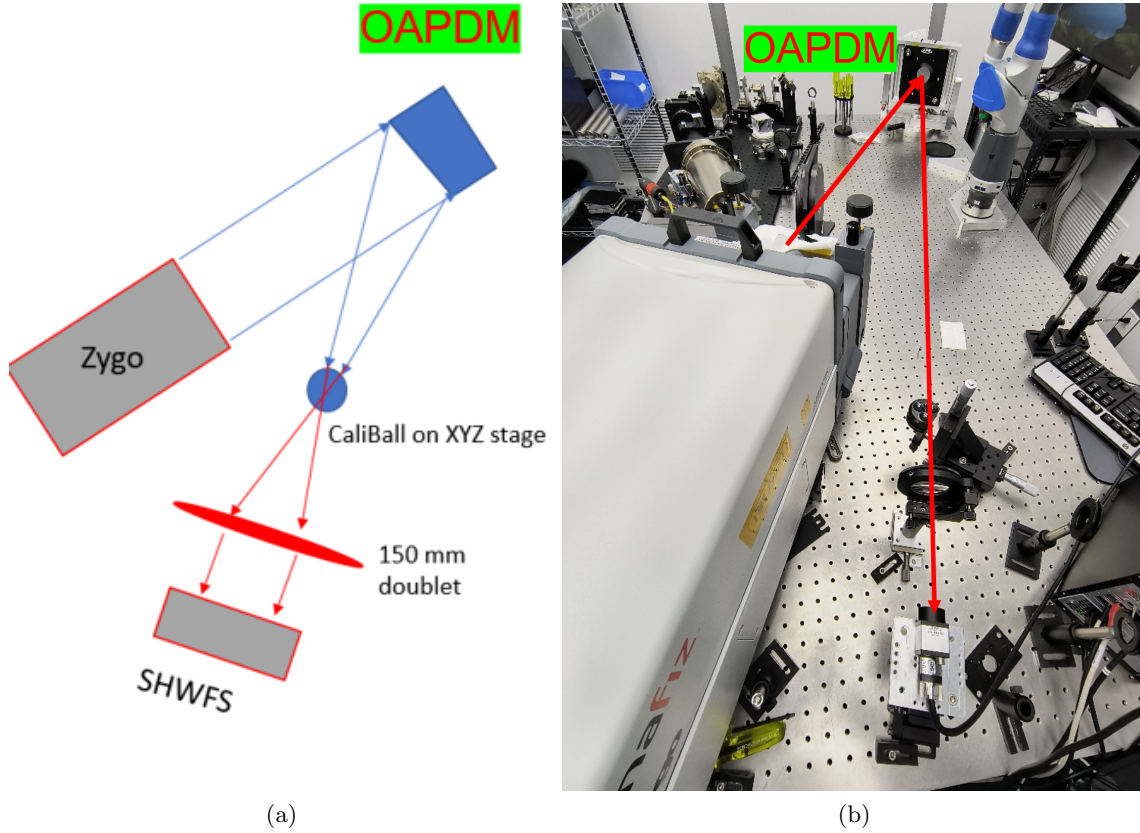


FIGURE 4: a) Sketch of the characterization testbed and b) image of the testbed.

engaged in a closed-loop configuration. This configuration enables real-time adjustments to be made to flatten the surface of the OAPDM, resulting in precise wavefront correction. Once the characterization is complete, we will integrate the OAP DM in the wavefront control testbed.

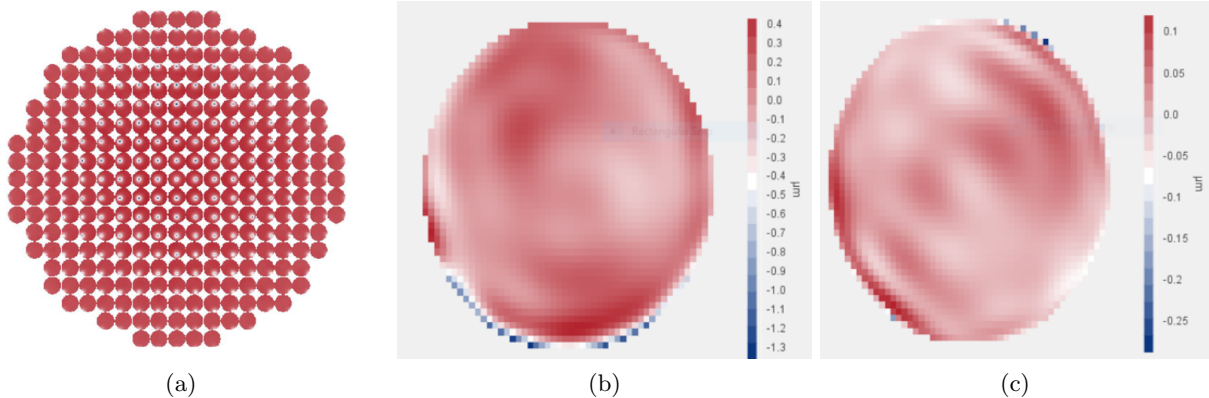


FIGURE 5: *OAP DM measurements. a) Influence function, b) powered DM shape with offset commands applied, and c) DM shape after applying flattening command in a closed loop.*

3.2 Wavefront Control Testbed

The primary purpose of this testbed is to verify the performance of the parabolic DM architecture. The layout of the proposed lab is shown in Fig. 3b. A laser source will be used as a starlight emulator. The light from the source is collimated using an off-axis parabola (OAP) manufactured by Space Optics Research Lab (SORL, Merrimack, New Hampshire, USA). A Physik-Instruments (PI, Auburn, Massachusetts, USA), tip-tilt stage with a 2-inch flat is placed at the first pupil. The focusing OAP after the tip-tilt mirror will be a deformable mirror OAP. By using multiple SORL OAPs of different focal lengths, multiple pupil access planes are created. The Boston Micromachines Corporation (BMC, Cambridge, Massachusetts, USA) 32×32 actuator DM is placed at the next pupil plane. The next pupil plane has an apodizer and if required, a Lyot stop will be at another pupil plane. At the coronagraph focal plane, a Zernike phase mask. This mask directs the rejected starlight to the low-order wavefront sensing (LOWFS) camera and the remaining light to the science camera. Details of these optical elements are presented in subsections 3.3 and 3.4. We are using metrology for coarse alignment and a 4D Phasecam interferometer (in double-pass) for fine alignment. The light from the interferometer is focused using a lens and the focus spot is used as a point source. The diverging light is collimated by the first OAP and a reflector is used in the beam path to reflect the light back to the interferometer for double-pass interferometry. To align focusing mirrors, we use a CaliBall sphere as a return. We repeat this process iteratively for all optics in the beam train to perform end-to-end alignment.

3.3 Apodizers

We have manufactured three coronagraph masks with average contrast of 10^{-9} over their respective dark zones (DZs). The first has a DZ of $4\lambda/D - 12\lambda/D$ (Fig. 6 a), the second spans $5\lambda/D - 13\lambda/D$ (Fig. 6 b), and the third covers $6\lambda/D - 24\lambda/D$ (Fig. 6 c). We manufactured the apodizer by using carbon nanotube technology at Lambda Consulting (Harwood, Maryland, USA) and GSFC. To manufacture a binary apodizer using this technology, the mirrors are fabricated from single-crystal silicon which is figured flat. A multilayer coating resistant to 750C growth temperatures is applied as a reflective layer. The apodizer pattern is laser written on the mirror coating to a few microns resolution. The photoresist on the mirror is developed and an ultra-thin layer of catalyst is applied. The residual catalyst is lifted from areas where no nanotube growth is desired, then the mirror is put in a tube furnace where carbon nanotubes are grown using a chemical vapor deposition process.

3.4 Focal Plane Mask/Zernike Phase Mask

The focal plane mask (FPM) design is shown in (Fig. 6 c). Each mask in the FPM has three different regions: 1) the reflective central phase disk of the FPM that has a diameter of 80 microns and depth of 80 nm, 2) a reflective region outside the phase disk, and 3) the outer bowtie shaped transparent region that lets transmits the light along the science path. The light that passes through the phase disk of the FPM acts as a reference wavefront and interferes with the light passing outside the phase disk which contains the information on wavefront aberrations.

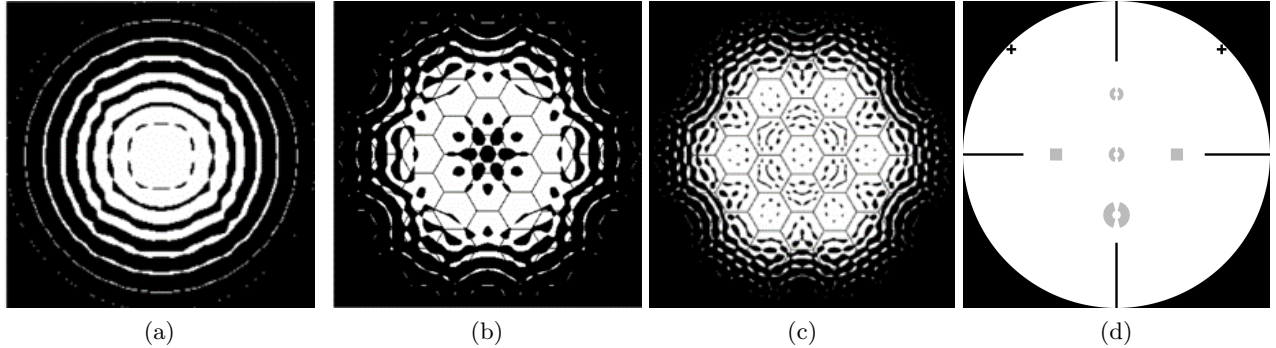


FIGURE 6: Apodizers. a) Apodizer optimized for a circular aperture, b) apodizer optimized for a segmented aperture to produce a smaller DZ, c) apodizer optimized for a segmented aperture to produce a larger DZ, and d) focal plane mask for the apodizers.

The interfered light is then relayed to another pupil plane, where the detector records the intensity pattern. This intensity pattern is related to the phase variation of the telescope pupil plane and depends on the size of the phase mask and the phase change introduced by this mask. Using the intensity pattern at the detector plane and the least-squares-fit algorithm, the low-order aberrations are inferred. This LOWFS is called a Zernike wavefront sensor.^{1, 3, 6, 7, 9, 11}

4. CONCLUSION

Wavefront control is essential for coronagraph-equipped direct imaging missions. Two flat deformable mirrors are used for wavefront control to achieve the required contrast needed to meet the mission objectives. We have shown that by making off-axis parabolic mirrors deformable, we can control wavefront aberrations to the desired level. Making the mirrors deformable reduces the number of actuators required, thus reducing the cost and risk of failure while increasing spectral bandwidth that can be corrected. We have worked with ALPAO to manufacture an OAP DM and have recently received a first-generation device. We are characterizing the DM and concurrently building a testbed to verify that the OAP DM could be used to dig dark holes.

5. ACKNOWLEDGEMENT

We would like to thank A J Riggs (JPL) for his contribution in designing the apodizer masks and John Hagopian (Lambda Consulting) for manufacturing the masks. The project is supported by NASA HQ-directed ExoSpec work package under the Internal Funding Scientist Model (ISFM) and NASA GSFC Internal Research and Development (IRAD) program.

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