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High-Contrast Spectroscopy Testbed for Segmented Telescopes

J.R. Delorme[a], D. Mawet[a,b], J. Fucik[a], J.K. Wallace[b], G. Ruane[a], N. Jovanovic[a], N.S. Klimovich[a], J.D. Llop Sayson[a], R. Zhang[a], Y. Xin[a], R. Riddle[a], R. Dekany[a], J. Wang[a], E. Choquet[b], W. Xuan[a], D. Encheverri[a], M. Randolph[a], G. Vasisht[b], B. Mennesson[b]

[a] Department of Astronomy, California Institute of Technology, 1200 E. California Blvd., Pasadena, CA, USA 91125;

[b] Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA, USA 91109;

ABSTRACT

The High Contrast Spectroscopy Testbed for Segmented Telescopes (HCST) at Caltech is aimed at filling gaps in technology for future exoplanet imagers and providing the U.S. community with an academic facility to test components and techniques for high contrast imaging with future segmented ground-based telescope (TMT, E-ELT) and space-based telescopes (HabEx, LUVOIR). The HCST will be able to simulate segmented telescope geometries up to 1021 hexagonal segments and time-varying external wavefront disturbances. It also contains a wavefront corrector module based on two deformable mirrors followed by a classical 3-plane single-stage coronagraph (entrance apodizer, focal-plane mask, Lyot stop) and a science instrument. The back-end instrument will consist of an imaging detector and a high-resolution spectrograph, which is a unique feature of the HCST. The spectrograph instrument will utilize spectral information to characterize simulated planets at the photon-noise limit, measure the chromaticity of new optimized coronagraph and wavefront control concepts, and test the overall scientific functions of high-resolution spectrographs on future segmented telescopes.

Keywords: Instrumentation, Testbed, Segmented Telescopes Simulator, High contrast imaging, Wavefront control, High Spectral Resolution, High Dispersion Coronagraphy

1. INTRODUCTION

The High Contrast Spectroscopy Testbed for Segmented Telescopes (HCST) has been designed to test high contrast imaging components and techniques in preparation for future segmented ground-based telescope, such as the Thirty Meter Telescope (TMT) and the European Extremely Large Telescope (E-ELT), as well as space-based telescopes including the Habitable Exoplanet Imaging Mission (HabEx)[1] and the Large UV/Optical/IR Surveyor (LUVOIR)[2] concepts. The HSCT is designed to replicate the realistic aperture geometries, observing conditions, adaptive optics, coronagraphs, and science instruments. The priority is to demonstrate starlight suppression technologies for segmented telescopes[3] and high dispersion coronagraphy (HDC) techniques.[4,5]

Alignment of the HCST is underway at the Exoplanet Technology Laboratory (ET lab.) described in section 2. Once completed, the testbed will be able to reproduce most of the future ground-based and space-based segmented telescopes as well as their extreme adaptive optic module thanks to its facility simulator describe in section 3. The HCST will be used by our team to demonstrate several high contrast imaging components described in section 4. Finally, the HCST will be open to collaborative experiments that aim to prepare high contrast imaging instruments for future segmented telescopes.

J.R. Delorme – E-mail: jdelorme@caltech.edu – Telephone: (1) 626 395 1571

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2. EXOPLANETS TECHNOLOGY LABORATORY

The ET Lab, located in the Cahill Center for Astronomy and Astrophysics at California Institute of Technology, is dedicated to the study and experimental validation of technologies used by the high contrast imaging community. It is a clean room (ISO class 7) where both temperature and humidity are well controlled. The laboratory is equipped with two optical tables. One is fully dedicated to the HCST, which is based on custom and high-quality optical components. Currently in the process of alignment, this version of the HCST will be operational by the end of summer 2017. Another version of the HCST called HCST-T, not described in this proceeding, is based on off-the-shelf optical components. Constructed during the summer 2016, this testbed is fully operational and was used to demonstrate the principle of the fiber injection unit[5] (also see Klimovich et al., these proceedings).

The reflective version of the HCST has been designed to maximize the Fresnel number of each optical with respect to the nearest pupil to enable precise wavefront correction with a deformable mirror located in a pupil plane. It is fully enclosed to minimize unwanted air turbulence. Most of the mounts are custom in order reduce the stress on each optic and maximize wavefront stability. The reflective optics, flat mirrors and off-axis parabolas (OAPs) are custom optics with protected gold metallic coating to ensure high optical throughput for experiments in the visible and infrared.

The HCST is divided in two parts: a dedicated facility simulator and an easily modified instrument testbed. The facility simulator, described in section 3, can reproduce most ground- and space-based segmented telescopes in order to test all relavant instruments and concepts for exoplanet science. Currently planned for 2017-2018 is an experimental validation of apodized vortex coronagraphs for segmented telescopes[3] described in section 4.1 and a fiber injection unit (FIU) dedicated to the Keck Planet Imager and Characterizer (KPIC[6]) described in section 4.2.

3. HCST FACILITY SIMULATOR

The HCST facility simulator, shown in Fig. 1, is divided in three modules: the star/planet simulator (in orange), the telescope simulator (in green), and the extreme adaptive optic (in blue).

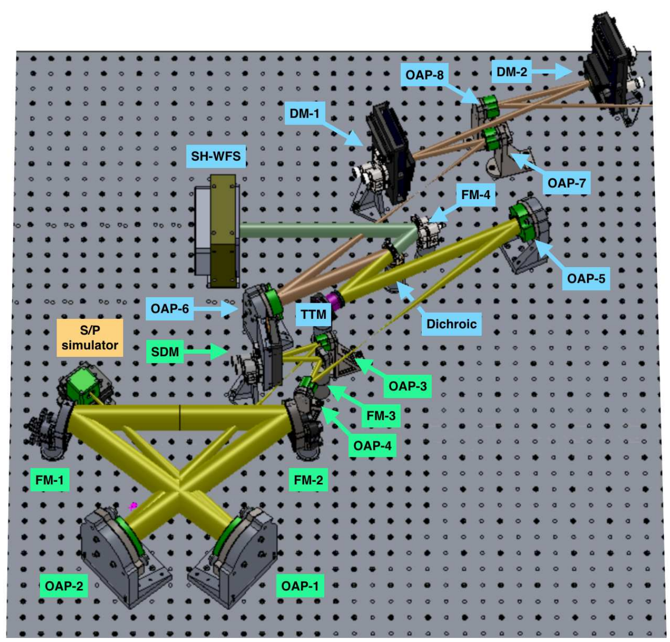

Figure 1. 3D model of the HCST facility simulator. It is divided in three modules: the Star/Planet simulator (in orange), the telescope simulator (in green) and the extreme adaptive optic (in blue).

3.1 Star/Planet Simulator

The purpose of the star-planet simulator is to generate a star and a planet with tunable angular separation, magnitudes, and spectra. The first design we plan to test is based on a beamsplitter and two single mode fibers: one to simulate the star and one to simulate the planet. Each fiber will be fed by a supercontinuum light source (0.4 to 2.4 μm). Before to inject the light in the input end of the fiber, we have the possibility to filter it and/or use a gas cell to modify the spectrum of either star or planet or both of them. In the star/planet simulator, the light of the two fibers is combined by a beamsplitter. The star light is reflected and the planet light transmitted. In this configuration, the planet beam is slightly affected by an astigmatism. After the star planet simulator, the light goes to the telescope simulator describe in the next subsection.

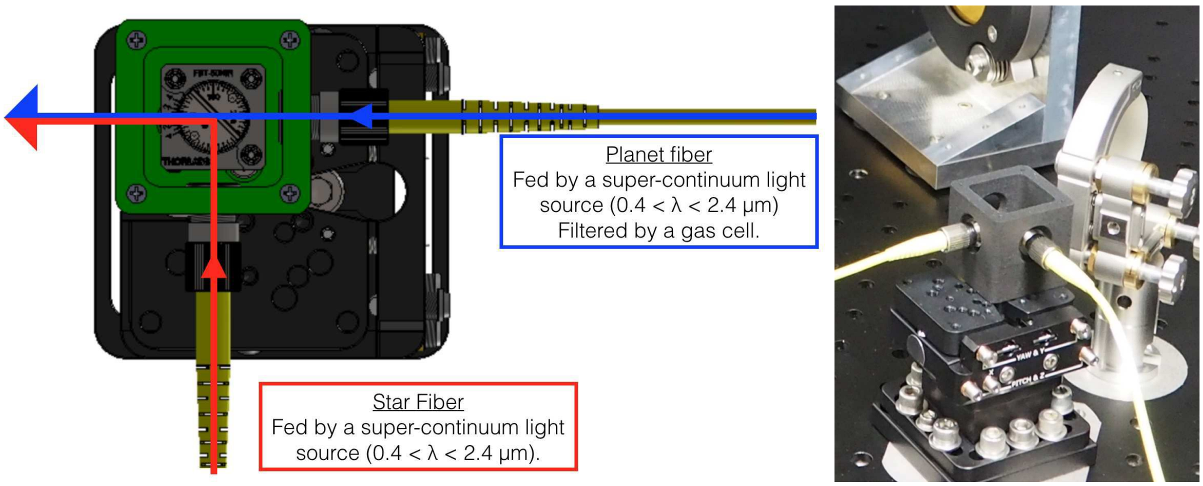

Figure 2. Left: top view diagram of the star/planet simulator. Right: picture of the star/planet simulator currently used on the HCST.

3.2 Telescope Simulator

The telescope simulator will be used to reproduce most of the actual and future ground-based and space-based segmented telescopes.

The first off-axis parabola of the optical layout, labeled OAP-1 on Fig. 1, climates the beam from the star planet simulator. Then the beam is reflected by two flat mirrors (FM-1 and FM-2). Between these two mirrors, we can, if we need to simulate a ground-based telescope, reproduce the effect of the atmosphere using a turbulence simulator based on phase plates (not shown in Fig. 1). We also define the main features of the telescope pupil (edges, spiders and central obscuration) between these two mirrors. After having been reflected by the second flat mirror (FM-2), the light will go through an optical relay composed of two off-axis parabolas (OAP-2 and OAP-3) before being reflected by a segmented deformable mirror (SDM). Its aim is to define the segments of the simulated telescope and reproduce the co-phasing error and missing segments. In order to reproduce these effects, each hexagonal segment of the segmented deformable mirror is fixed to three actuators able to introduce tip, tilt and piston. Because the current and future ground-based and space-based segmented telescopes have a various number of segments, we have three different segmented deformable mirrors able to reproduce most of the segmented telescopes. These mirrors are shown by the Fig. 3. From the left to the right, we have:

- a PTT111-L5 (37 segments) manufactured by Iris AO. With this segmented DM, we can simulate JWST (18 segments), Grand Telescopio Canarias (36 segments), Keck (36 segments).
- a PTT489 (163 segments) manufactured by Iris AO. With this segmented DM, we can simulate LUVOIR (120 segments).
- a Hex-3063 (1021 segments) manufactured by Boston Micromachines Corporation. With this segmented DM, we can simulate TMT (492 segments) and the E-ELT (798 segments).

The packaging of the PTT111-L5 and the PTT489 are very similar so we can use the same optical layout for both of them. To use the Hex-3063, which is much bigger, we need to use another design of the HCST based on the same optics and components. The optical layout presented in this proceeding is compatible only with the Iris AO DMs.

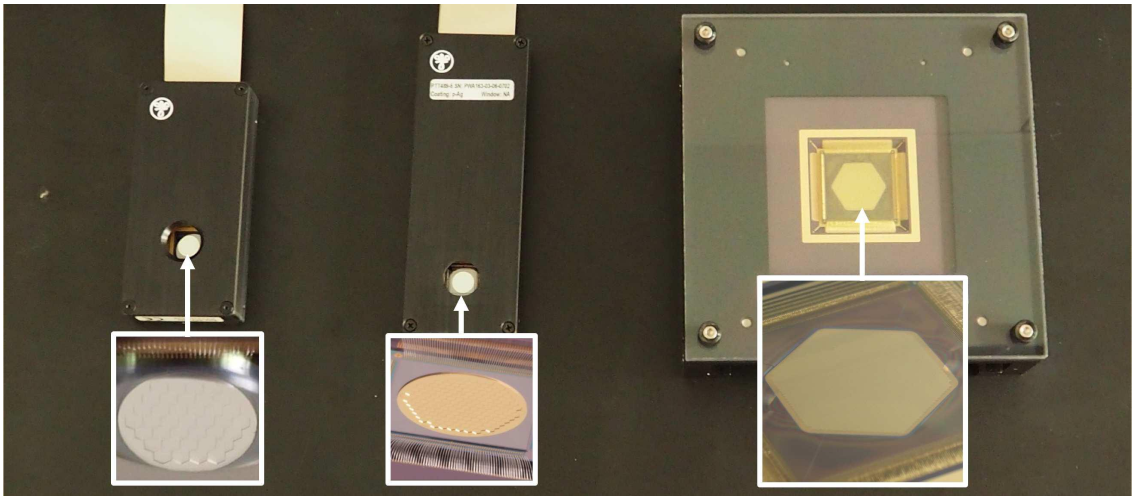

Figure 3. Segmented deformable mirrors available for the HCST. From the left to the right: PTT111-L5 (37 segments) and PTT489 (163 segments) manufactured by Iris AO and Hex-3063 (1021 segments) manufactured by Boston Micromachines Corporation.

After the segmented DM, the light is reflected by a flat mirror (FM-3) and focus by an off-axis parabola (OAP-4). The focal plane downstream this OAP is the focal plane of the telescope simulator.

3.3 Extreme Adaptive Optic

The goal of the extreme adaptive optic module is to correct the phase and amplitude aberrations. Located downstream from the telescope simulator, an off-axis parabola (OAP-5) collimates the beam in the direction of a tip-tilt mirror (TTM) based on a fast steering piezo actuator manufactured by Physics Instrument. The light reflected by this optic is then divided by a dichroic. The visible part of the light is transmitted and goes to a Shack-Hartmann wavefront sensor (SH WFS) while the rest of the light goes through an optical relay based on two off-axis parabolas (OAP-6 and OAP-7). In the pupil plane downstream from the OAP-7, a first Kilo-DM manufactured by Boston Micromachines Corporation is used to correct the phase aberrations. This first deformable mirror is followed by a second one. Located in a collimated beam but not in pupil plane, this one is used to correct the amplitude aberrations. The two Kilo-DMs (DM-1 and DM-2) and the tip-tilt mirror will be controlled by the Shack-Hartmann wavefront sensor using a real-time computer. The software used will be the one used by the Robo-AO project.[7,8] After these two DMs, the light is collimated by the last off-axis parabola of the facility simulator (OAP-8).

4. INSTRUMENTS FOR SEGMENTED TELESCOPES

A large part of the testbed is dedicated to test instruments and concepts for segmented telescopes. Before openning the HCST to collaborations, we plan currently to do several tests. The two main tests planned are the test of apodized vortex coronagraph for segmented telescopes (paragraph 4.1) and then the test and characterization of most of the components of the Keck Planet Imager and Characterizer (paragraph 4.2).

4.1 Apodized Vortex Coronagraph for Segmented Telescopes

The first concept tested with the HCST will be an apodized vortex coronagraph for segmented telescopes (also see Ruane et al., these proceedings). This coronagraph is a promising solution that theoretically meets the performance required by the future segmented space telescopes for high contrast imaging. The idea here is to verify its performances in lab. Fig. 4 presents one of the optical layouts designed for this test*. The light from the facility simulator is collimated by an off-axis parabola (OAP-9). In the following pupil plane, the light is reflected by an apodizer before being focused by another off-axis parabola (OAP-10) on a vortex phase mask[9–11] located in the focal plane of this OAP. Downstream from the phase mask, the light is collimated by an off-axis parabola (OAP-11) before to be reflected by two flat mirrors (FM-4 and FM-5) and focused by the last off-axis parabola (OAP-12) on the science detector. The Lyot stop of the coronagraph located in the pupil plane between the two flat mirrors will reflect the stellar light diffracted by the coronagraph in order to feed a Lyot based low order wavefront sensor (LLOWFS[12]) not shown in Fig. 4.

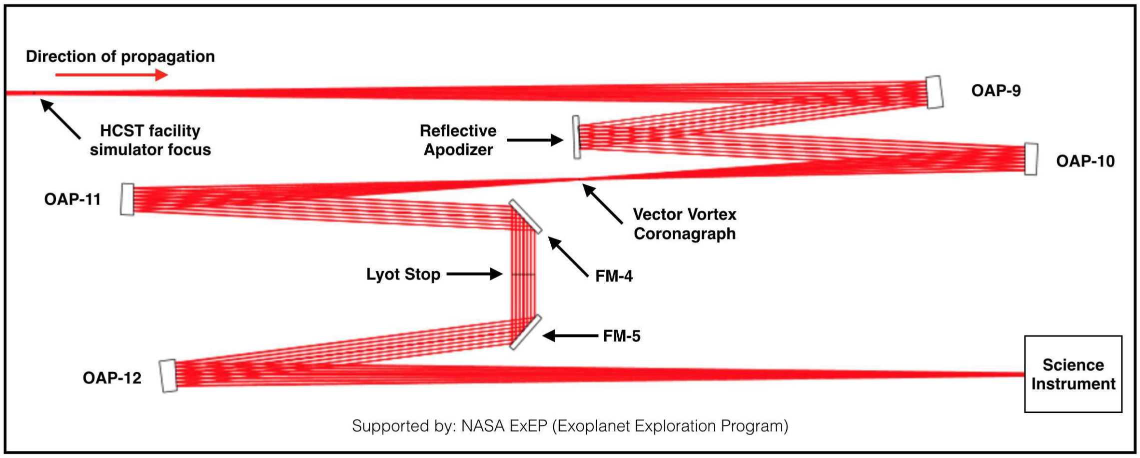

Figure 4. Optical layout design to test the apodized coronagraph for segmented telescopes.

This experiment will be used to study the effect of segmented apertures, co-phasing errors and missing segments on the coronagraph performance in order to optimize the coronagraph design of the future segmented telescopes.

4.2 Keck Planet Imager and Characterizer

The Keck Planet Imager and Characterizer (KPIC) presented by Fig. 5 consists of an upgrade to the Keck II AO system and instrument suite. It is equipped with an infrared pyramid wavefront sensor, a high-order deformable mirror, a coronagraph, and a fiber-injection unit (also see Mawet et al., these proceedings). The goal of KPIC is to suppress the starlight and feed the light from an exoplanet into a single mode fiber in order to spectrally characterize the planet using the high resolution spectrograph NIRSPEC.[13] All modules of KPIC expected the infrared pyramid wavefront sensor will be tested and characterized using the High Contrast Spectroscopy Testbed for Segmented Telescopes before being transferred to the Keck II telescope.

5. CONCLUSION

Currently in its phase of integration, the High Contrast Spectroscopy Testbed for Segmented Telescopes will be operational before the end of the summer. Once aligned, the HCST will be able to simulate ground-based and space based segmented telescopes up to 1021 hexagonal segments. During the first few months following the integration phase, we plan to test apodized vortex coronagraph for segmented telescopes in order to investigate if this coronagraph can meet the high contrast imaging with future segmented space telescopes. Then we will test and characterize most of the Keck Planet Imager and Characterizer modules before sending them to the Keck II telescope. Finally after this phase, the HCST will be open to collaborations with the aim of preparing high contrast imaging instruments and techniques dedicated to current and future segmented telescopes.

*Several optical layout based on the same optics have been designed in order to test a large number of coronagraphs

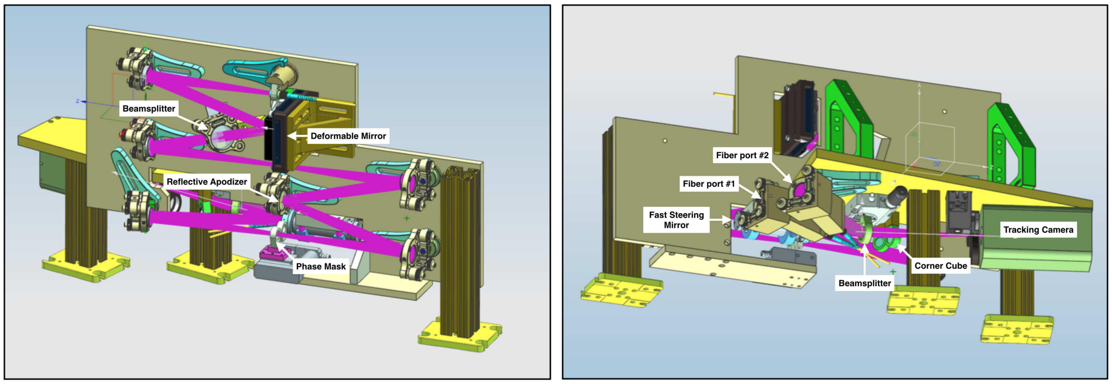

Figure 5. Front side (left) and back side (right) of a 3D model of KPIC. The infrared pyramid wavefront sensor is not shown.

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