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Pyramid wavefront sensing developments at NRC-HAA

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ABSTRACT

Many next generation adaptive optics (AO) systems, on both 10-m class telescopes and future giant segmented telescopes, plan to incorporate a pyramid wavefront sensor (PWFS) to achieve their performance requirements. As a significant number of the instruments being developed at National Research Council Canada Herzberg Astronomy and Astrophysics Research Centre (NRC-HAA) contain a PWFS, we have re-established a PWFS testbed. We present the design for the AO PWFS bench and first light results. A key design of the bench is the portability of the PWFS arm such that it can be installed on NRC-HAA's local AO system for on-sky testing of the PWFS with the Herzberg Extensible Adaptive optics Real-time Toolkit as the real-time controller.

Keywords: Pyramid wavefront sensing, R&D, on-sky testing, optical gain, time-resolved wavefront sensing, REVOLT, REVOLT-COPPER, HEART

1. INTRODUCTION

National Research Council Canada Herzberg Astronomy and Astrophysics Research Centre (NRC-HAA) is involved in various adaptive optics (AO) projects making use of the pyramid wavefront sensor (PWFS) [17] including the Thirty Meter Telescope's (TMT) facility AO system NFIRAOS (where the PWFS will be used as a truth wavefront sensor [16, 2]) and the real-time control (RTC) system for Gemini Planet Image upgrade, GPI2 [13]. To support these developments and other projects, we have re-established a PWFS bench. The testbed will support various new instruments by testing algorithms and pipelines in advance of complete system integration as well as support local PWFS research and development (R&D) efforts.

The PWFS provides more sensitivity than other wavefront sensors (WFS), such as the Shack-Hartmann WFS (SHWFS), with greater sensitivity leading to improved performance of an AO system. The resulting performance improvement means higher sky coverage, better image quality, and enhanced contrast. For this reason, the PWFS has been planned in many new AO systems. With the promise of more sensitivity and better

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AO performance comes challenges. The PWFS is inherently a non-linear WFS [11]. Therefore, work needs to be done to understand how to operate the PWFS on-sky to take full advantage of its theorized performance limits and realize a better-performing AO system. The new PWFS testbed aims to improve the technology readiness level (TRL) of the PWFS at NRC-HAA and reduce the risk for current and future projects at NRC-HAA. Taking advantage of previous PWFS laboratory work at NRC-HAA [16, 15, 6, 14, 5], this project will move forward from the demonstration of fundamental properties of the PWFS to critical R&D to maximize the PWFS performance, such as the time-resolved wavefront sensing [1, 4] and non-linear phase reconstruction of the PWFS using machine learning techniques [8]. It will also enable testing of optical gain calibration and comparing the baseline algorithm for instruments such as NFIRAOS [15, 6] to the latest methods proposed by the broader AO community such as the gain scheduling camera [9]. Furthermore, the testbed will move to on-sky testing of the PWFS on the local AO system, REVOLT.

REVOLT (Research, Experiment and Validation of Adaptive Optics with a Legacy Telescope) [12] is an AO system on the 1.2 meter telescope in Victoria, B.C., Canada that makes use of NRC-HAA's real-time-control (RTC) solution: Herzberg Extensible Adaptive optics Real-time Toolkit (HEART)[10]. Having successfully demonstrated closed-loop operation with a SHWFS using a C-blue-one detector, REVOLT achieved a Strehl ratio of 33% in H band. On-going upgrades to REVOLT include an open-loop WFS demonstrator (REVOLT-GOLD) to test algorithms for Gemini's GIRMOS instrument currently being built at the University of Toronto [7] as well as testing new features of HEART as they become available. For the remainder of this paper, we will discuss the evolution, optical design, and laboratory results for REVOLT-COPPER (Canadian On-sky Platform for PWFS Experimental Research): a PWFS upgrade to REVOLT.

REVOLT-COPPER is a portable arm of REVOLT to deploy a PWFS on-sky. It is portable because the optics can easily be moved between a laboratory setup (running either HEART or a slower interface using MATLAB) and the optical bench located at the 1.2m telescope. This flexibility allows us to move the setup as needed and perform various experiments. While at the 1.2m, REVOLT's internal light source can also enable R&D. In Section 2, we present the optical layout of the PWFS in the AO laboratory at NRC-HAA and how it relates to the optical design of REVOLT-COPPER presented in Section 3. The status of the PWFS and first light results are then presented, see Section 4, followed by a discussion of the future work that will be done using the PWFS in Section 5.

2. DESCRIPTION OF PWFS BENCH

Figure 1 shows the PWFS bench in the AO laboratory at NRC-HAA. The PWFS was installed at the beginning of 2023. We use a 635nm laser diode as our light source, and the beam height in the laboratory matches the REVOLT's optical height. The light hits the ALPAO 97 actuator deformable mirror (DM), which defines the pupil. The beam moves around the bench with two empty pupil planes, one for a potential future spatial light modulator (SLM) and the other for moving phase plates to simulate turbulence. A beam splitter then sends some of the light to a HASO SHWFS, and the rest of the light goes to the PWFS arm, where the incoming f-number to hit the Physik Instrumente (PI) fast steering mirror (FSM) is selected to match the f-number delivered by REVOLT to REVOLT-COPPER. The PWFS optic is one of the double pyramids manufactured by BMV Optical (in Ottawa, Canada) for NFIRAOS [2, 3]. The PWFS has a custom mount on a cage system that contains a fore-optic, 8/92 beam splitter, and optic after the PWFS to get the correct pupil size on the PWFS camera: an Andor Zyla 5.5 camera. The 8/92 pellicle beam splitter sends 92% of the light to PWFS and 8% of the light to a focal plane camera that allows us to perform image sharpening to provide a sharp point-spread-function (psf) to the PWFS, calibrate and monitor the modulation path produced by the FSM, and in the future be used for optical gain calibration (gain scheduling camera [9]). Currently, the camera is a simple USB FLIR Grasshopper3 camera that can run at a maximum of 163 Hz at full frame. The FSM and Zyla triggering is performed using a data acquisition (DAQ) card (specifically Adlink DAQ/PXI-2501) and had previously been used for a flattened PWFS experiment [5]. The DAQ has four analog output channels (AOC; ± 10V bipolar) with a 1 MS/s output rate and an 8K samples FIFO (first-in-first-out) buffer that can store voltages in a table and be infinitely looped over. Since the four AOC channels share one clock and buffer, we use two of the AOCs to drive the two FSM axes, while a third AOC is used to generate the TTL signal for the Zyla camera, which is used to trigger the start of an exposure. The Zyla is used in global shutter mode and with an area of interest (AOI) of 128x128 pixels being read, allowing us to achieve frame rates of over 700 Hz operating in overlap mode (exposing while reading out frame). For the PWFS, we have 26 pixels across the pupils for a total of 540 pixels over the entire pupil.

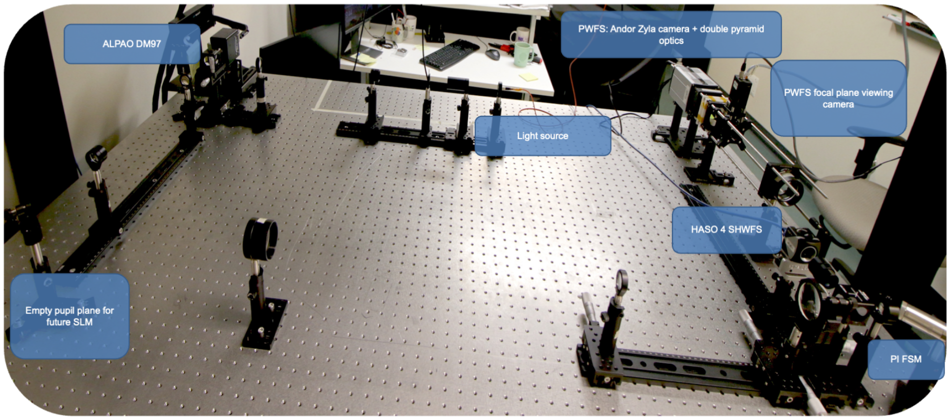

Figure 1. Picture showing the PWFS in the AO laboratory at NRC-HAA with key components labeled.

3. REVOLT-COPPER

REVOLT is located in the Dominion Astrophysical Observatory (DAO) 1.2m telescope's coude room where the McKellar spectrograph is located. The layout of REVOLT is shown in Figure 2, which illustrates the original REVOLT optical paths: the common path, the SHWFS path (blue) and the science path (red). With a median seeing of approximately 2.1", REVOLT uses 17 actuators across the pupil controlled by a leaky integrator with input from the 16x16 lenslet array SHWFS. Wavefront sensing is done in the visible with the science path observing J and H bands [12]. In Spring 2023, the open loop WFS path REVOLT-GOLD [7] (gold/yellow path in Figure 2) was installed, with on-sky testing commencing in Summer 2023. Note that the open-loop path is a copy of the closed loop SHWFS. REVOLT-COPPER is shown in green. The F/20 beam feeding the PWFS arm is mimicked on the laboratory setup, allowing us to take the FSM and PWFS optics—mounted in a cage—and directly place them on REVOLT and connect the camera to the HEART RTC, and control the FSM mirror from a Windows computer housing the DAQ card.

The PWFS will operate on-sky using a version of the Gemini Planet Imager 2's (GPI2) HEART pipeline to test the RTC on-sky ahead of operation on GPI2 [13]. The PWFS pixels are read in and converted directly to modes. There is an option to apply optical gains to the modes and non-common path subtraction via the modes. The leaky integrator is applied in modal space and then the modes are converted into DM space.

4. STATUS AND FIRST LIGHT

On the PWFS bench in the laboratory, the HASO SHWFS acts as a true wavefront sensor and performs the initial DM flattening as the DM's factory flat is outside the PWFS capture range. Previous flats from other optical setups using the same DM were no longer available. Using the HASO reconstructed wavefronts, we flatten the DM. The FLIR focal plane camera in front of the PWFS can then be used to view the quality of the flat and further improve upon it via focal plane sharpening. This was done to get the final alignment of the PWFS and provide a flat wavefront to the PWFS until the modulation and camera synchronization were completed and the FSM calibrated.

4.1 FSM calibration

One key component to the successful operation of the PWFS is the calibration of the FSM. Our FSM has two axes clocked 45° from the optical axis of the bench. With an angle of incidence of 45° , the FSM axes have an

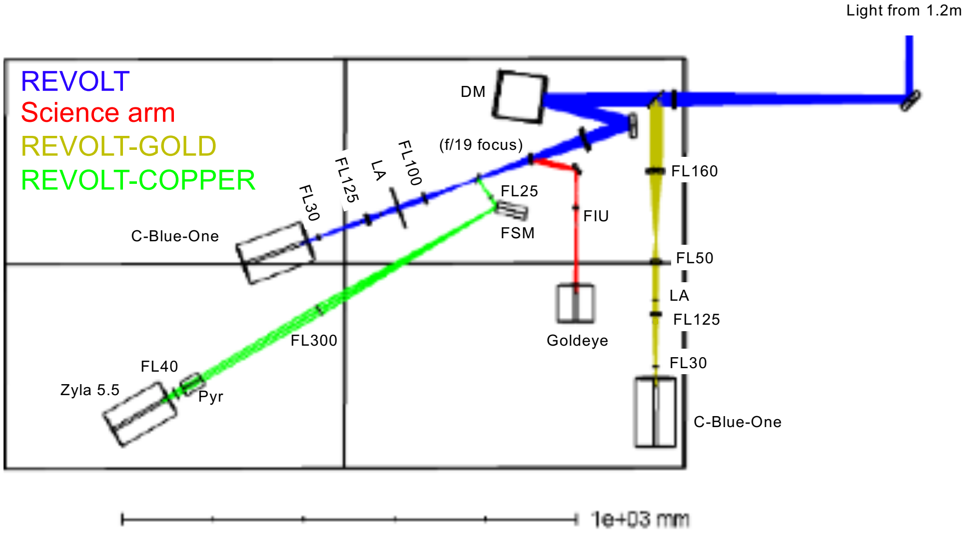

Figure 2. Optical layout of REVOLT, REVOLT-GOLD, and REVOLT-COPPER on the 1.2m telescope located at the DAO in Victoria.

angle between the two axes of 70° instead of 90°, and therefore, the two axes are no longer orthogonal to each other. This is shown in the left image of Figure 3 where we measure the angle between the two axes to indeed be 70°.

To calibrate the two axes, we directly find the correction that should be applied to the FSM for a given modulation path at a given frequency. We measure the path taken by the FSM for pure sine and cosine inputs on the two axes, as shown in Figure 3 (middle). We then fit an ellipse to the path taken, including the semi-major and -minor axes and clocking angle. We note that for a pure sine and cosine input to the FSM, the modulation path achieved at different frequencies, including the clocking angle, varies dramatically. We then change the inputs to the FSM axes to match the measure ellipse, which provides us with a more circular modulation path as seen in Figure 3 (right). We are still working on improving the calibration to generate a more circular path.

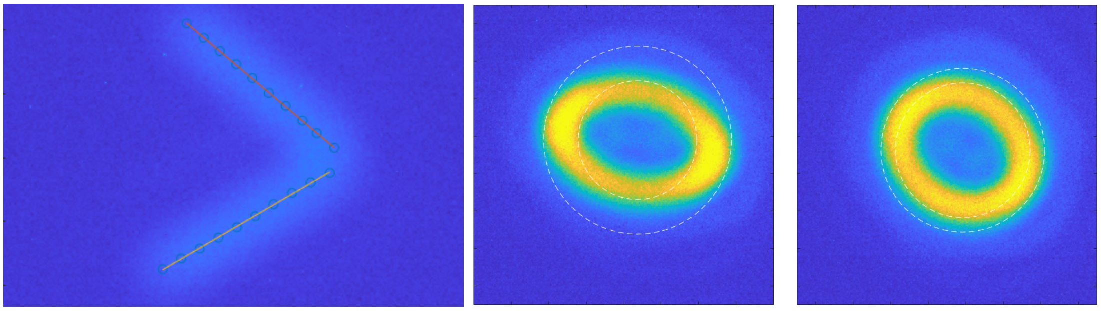

Figure 3. FLIR camera images showing: (left) the summed image for various steps along one axes and then the other along with a linear fit to the corresponding psf centers; (middle) modulation path for without any correction; (right) modulation path with correction. White dashed lines show example circular paths for reference. Note we still have a slight elongation in the corrected case.

4.2 Closed-loop operation

With the FSM calibrated and the synchronization of FSM and Zyla camera, we were able to close the loop with the PWFS to flatten the DM further. To start, we are using a zonal interaction matrix with a integrator. Figure 4 shows a flat (with no modulation) achieved with a 3 λ/D modulation radius. Here, a small amount of residual tip/tilt can be removed after a cascading flattening protocol where we start with a modulated PWFS and then further remove aberrations with non-modulated PWFS. We also can use the psf camera for image sharpening if there is a large static aberration or use the HASO SHWFS, assuming the aberrations are not non-common-path aberrations between the two wavefront sensors.

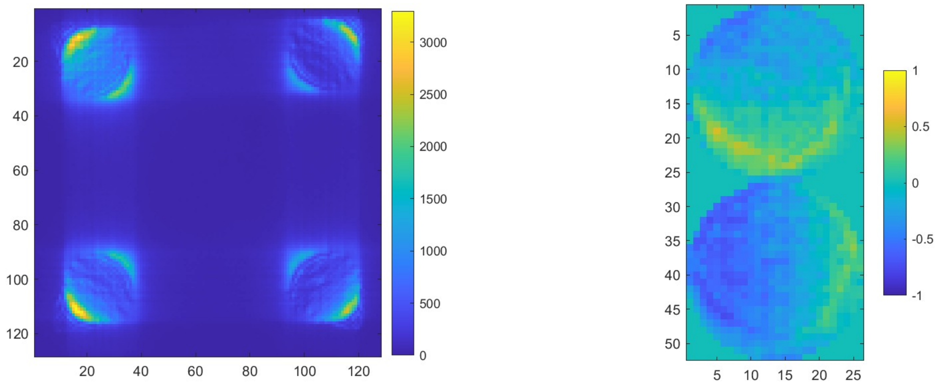

Figure 4. Flattened PWFS image (left) with the corresponding slopes with no modulation (right).

After flattening the wavefront, we removed larger static aberrations and finally removed evolving turbulence. Using OOMAO to generate atmospheric turbulence, we apply turbulence on the DM corresponding to a 1.2-m telescope with an r0=10 cm and wind speed of 5 m/s, evolving it at 500 Hz. The starting psf, open loop psf, and closed loop psf are shown in the upper panel of Figure 5 with the corresponding PWFS images in the lower panel.

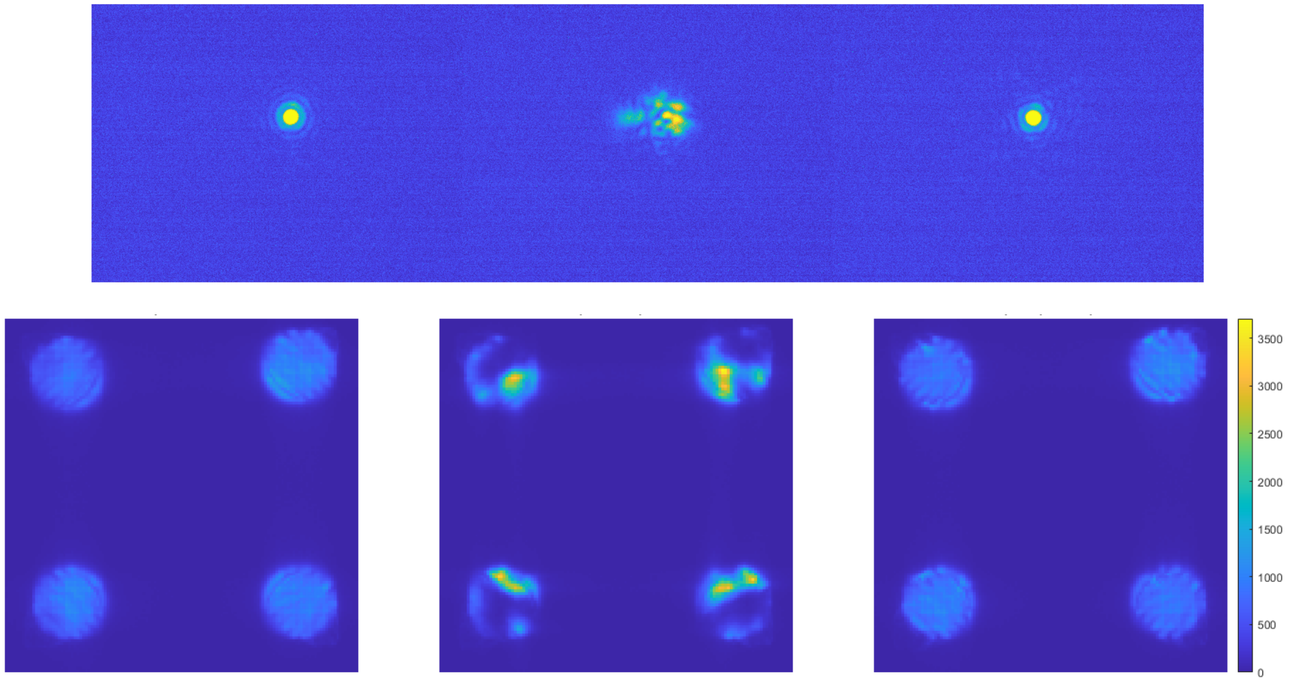

Figure 5. Example of the PWFS operating in closed-loop showing the psf and PWFS image for a flat wavefront, before the loop is closed, and after the loop is closed using 3 λ/D modulation radius.

5. FUTURE WORK

With a working PWFS set up in the laboratory, we are working towards moving the system to REVOLT in the Fall of 2023, with on-sky opportunities at the end of October and November 2023, respectively.

To achieve first light on-sky, we are currently working on getting the PWFS running with HEART in the laboratory, which will replicate how the PWFS will be run on-sky. The PWFS pipeline takes in pixels from the camera, and the reconstructor goes directly from pixels to modes where modes offsets are applied before moving into DM space where the controller is applied. We are also in the process of testing the final camera readout speed. We have verified the DAQ card speed and the camera up to 450 Hz using MATLAB but need the infrastructure of HEART to measure the frame rate up to 700 Hz accurately. Then, at the beginning of October 2023, we will move the PWFS to REVOLT.

After on-sky testing in the Fall of 2023, we will use Winter 2023 for some R&D work, including testing the gain-scheduling camera. Note that winter weather is typically poor in Victoria, B.C., preventing most observing. REVOLT has an internal light source so the system can act like a laboratory during the day. For the gain scheduling camera to run faster, we are investigating using a second Zyla 5.5 camera, already at NRC-HAA, that could run quickly and be synchronized with the existing setup using the last AOC channel. We will also work on time-resolved wavefront sensing. The DAQ card functionality was developed to trigger multiple exposures per modulation cycle, which has been tested and verified in the laboratory, enabling the time-resolved work. Finally, on longer timescales, Spring 2024 observing runs with REVOLT-COPPER will enable further testing of the PWFS pipeline in HEART and testing of any new features.

6. CONCLUSIONS

In the last nine months, we have designed, built, and tested our PWFS in the laboratory at NRC-HAA using the existing hardware from previous PWFS setups. We successfully closed the loop with a modulated PWFS. In Fall 2023, the PWFS bench will be moved to the 1.2-m telescope forming REVOLT-COPPER, where we will test the PWFS pipeline of the RTC, HEART, for the first time on-sky. Using the internal light source on REVOLT, we will continue R&D efforts: testing optical gain algorithms and new wavefront sensing ideas, including time-resolved wavefront sensing.

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