# Zernike wavefront sensor measurements for a full CGI characterization

**Type of observation:**
☒ Technology Demonstration
☐ Scientific Exploration

**Scientific / Technical Keywords:** high contrast performance

**Required Detection Limit:**

| $\geq 10^{-5}$ | $10^{-6}$ | $10^{-7}$ | $10^{-8}$ | $10^{-9}$ |
|---|---|---|---|---|
| | | x | x | x |

Note: For this demonstration, any contrast at a level better than $10^{-7}$ would be necessary. This is **raw contrast**, as post-processed contrast is not meaningful in the proposed demonstration.

**Roman Coronagraph Observing Mode(s):** These observations require an unsupported mode where the ZWFS mask is used in the focal plane. This mode ie being discussed in the CPP hardware working group for a possible implementation. Simulations are under way to understand if the LOWFS can be used in parallel of such observations or if totally open-loop observations are the only viable option.

| Band | Mode | Mask Type | Coverage | Support |
|---|---|---|---|---|
| 1, 575 nm | High-order ZWFS | SPAM: OPEN<br>FPAM: HLC12_C7R2:8<br>LSAM: OPEN<br>FSAM: OPEN<br>CFAM: 1F<br>DPAM: Pupil Imaging Lens | N/A | Unsupported |

**Summary:** The Zernike Wavefront Sensor (ZWFS), based on Frits Zernike's phase contrast method, is a highly sensitive tool used in high-contrast imaging (HCI) to convert small wavefront errors into intensity variations. ZWFS systems have already demonstrated sub-nanometer accuracy in both testbeds and ground-based instruments for the estimation and compensation of quasi-static aberrations.

CGI incorporates a ZWFS for the LOWFS, but it is spatially-filtered and is therefore only sensitive to very low-order aberrations. In this technology demonstration white paper, we propose to use the existing semi-reflective ZWFS within EXCAM's focal plane mask substrate to enable measurement of all spatial frequencies, up to the deformable mirror's cutoff and beyond. Three key goals drive this proposal: characterizing the deformable mirror's in-flight behavior and long-term stability, detailing the observatory's (OTA) stability to identify ultimate contrast limitations, and enhancing micrometeoroid detection through sub-nanometer phase error measurements in the pupil. Observations require a bright single star and a baseline pupil image without the mask; exposure times vary depending on whether characterizing the DM, monitoring OTA stability (requiring prior dark hole digging), or detecting micrometeoroids. If implemented before launch, these observations are highly valuable for commissioning and early science phases, providing critical insights to optimize observing strategies.

**Table of Example Targets:**

The proposed observations need a very bright *single* star. The star can be one of the reference stars used to dig the dark hole for standard science observation sequences.

| Name | Host star V mag. | Detection limit | Separation (") (or extent) | Description of target |
|---|---|---|---|---|
| Any | $V < 5$ | | | Bright, single star |

## Anticipated Technology / Science Objectives:

The Zernike wavefront sensor (ZWFS), based on the phase contrast method originally developped by Frits Zernike [1], has found direct applications in high-contrast imaging (HCI) due to its simplicity of implementation and high sensitivity [2]: in short, it converts small phase errors of the incoming wavefront into small intensity variations in the pupil. This property becomes essential in HCI applications when these small phase errors affecting the wavefront translate into speckles in focal-plane images, which can vary over different timescales and ultimately limit the contrast that can be reached in raw and post-processed images [3]. ZWFS are now routinely implemented in testbeds [4, 5, 6] or in ground-based facility instruments [7, 8], where they have demonstrated their ability to measures phase errors with sub-nanometer accuracy. The ZWFS is also the solution that has been adopted by CGI for low-order wavefront sensing (LOWFS) on LOCAM by using the light reflected on the focal-plane mask (FPM) of the hybrid Lyot coronagraph [9]. However, this WFS is only sensitive to low-order aberrations because it is spatially filtered by the physical size of the FPM.

In this white paper, we propose using another ZWFS mask, which is embedded in the FPM substrate, to enable high-order wavefront sensing using EXCAM. Such measurement would be sensitive to all spatial frequencies (up to the DM cutoff and beyond) since this additional mask is not spatially-filtered. It is also semi-reflective, which should enable using the LOWFS in parallel (this is currently being confirmed with dedicated simulations with `cgisim`), therefore closely imitating standard science observations. The measurements have three goals:

1. **DM characterization:** Measurements at the picometer accuracy are idea to characterize the DMs behaviour in-flight (Fig. 1). Moreover, regular measuements over the course of the mission would enable monitoring any evolution of DM behaviour or degradation. This type of studies is critical to understand the long-term stability of DM hardware in preparation for HWO.

2. **OTA stability:** The final post-processed contrast is highly dependent on the stability of the dark-hole, which directly relates to the stability of the optical telescope assembly (OTA) and aberrations in CGI. Using time series of measurements taken over the course of a few hours, the ZWFS would uniquely enable a detailed understanding of the stability of the observatory and of the ultimate limitations in contrast. This type of time series measurements has been performed on ground-based facilities (Fig. 2), so the framework to in-

terpret similar measurements in CGI is already in place. This is also the only opportunity to measure the stability of an HCI instrument located at $\mathcal{L}2$.

3. **Pupil images as a micrometeoroid counter:** While a ZWFS is not strictly needed to monitor micrometeoroids impact in pupil images, it has the added value of providing sub-nanometer phase error measurements at the location of the impacts. If the ZWFS mode is supported, using it instead of simple pupil imaging can only be beneficial.

Software for the analysis of ZWFS data is readily available with the pyZELDA python package, which has been designed to handle any ZWFS data.

**Is this observation appropriate for "first-look" / commissioning, the observation phase , or a potential extended observing phase?**:

The ZWFS measurements require this specific mode to be supported. If this support can be implemented before launch, then the observations are certainly appropriate for commissioning or early observations. They have the potential to tell us a lot about the behaviour of the OTA and of CGI, which can have a direct impact on the observing strategy for astrophysical observations.

## Observing Description:

Since there are multiple applications for ZWFS measurements, it is difficult to describe in detail a standard observation. There are, however, some requirements: 1/ the observations must be done on a bright single star to maximize the SNR of pupil images, and 2/ a pupil image without the mask in place must be acquired to be able to accurately convert the ZWFS measurements into phase.

Apart from these requirements, the observation depends on the goal: for DM characterization, several measurements with different DM pokes would need to be acquired (1 measurement per poke); for OTA stability, we would keep taking data for as long as we want to characterize OTA and instrument; and for micrometeoroids counting, single measurements are necessary.

**Estimate of Time Needed**: The exposure time will strongly depend on the goal of a given observation. For OTA stability characterization, the dark hole digging must have been performed beforehand to really monitor the variations with respect to the optimal DM shapes that provide the highest possible raw contrast. For the other technical goals, the dark hole requirements are still to be defined.

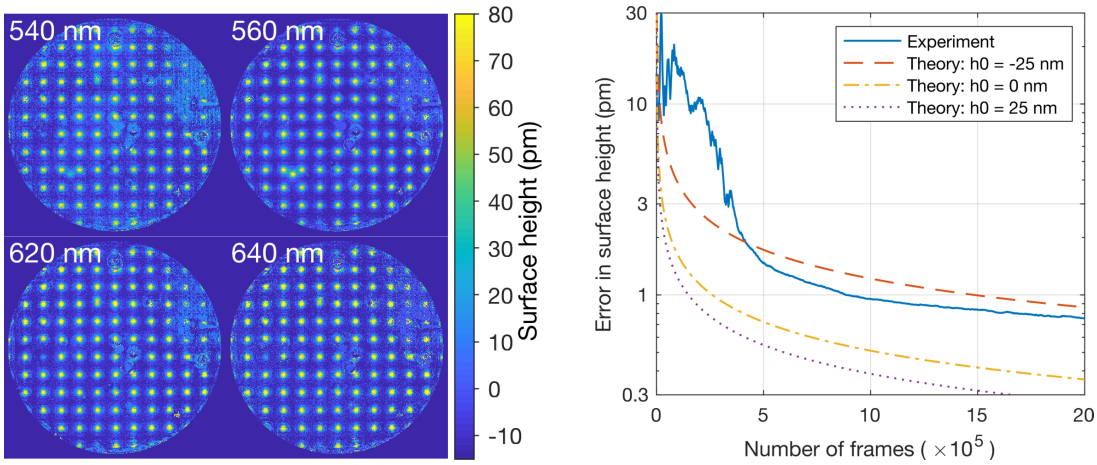



Figure 1: Example of ZWFS measurement on the Decadal Survey Testbed [4] that show DM pokes measured at different wavelengths (left) and demonstrate that this type of sensors can measure low- and mid-spatial frequency aberrations up to the control limit of the deformable mirror, with surface height sensitivity as small as 1 pm (right). Our proposed measurements could uniquely enable to monitor the health of the CGI DMs over the life the observatory by identifying any degradation of performance in stroke, linearity, etc.

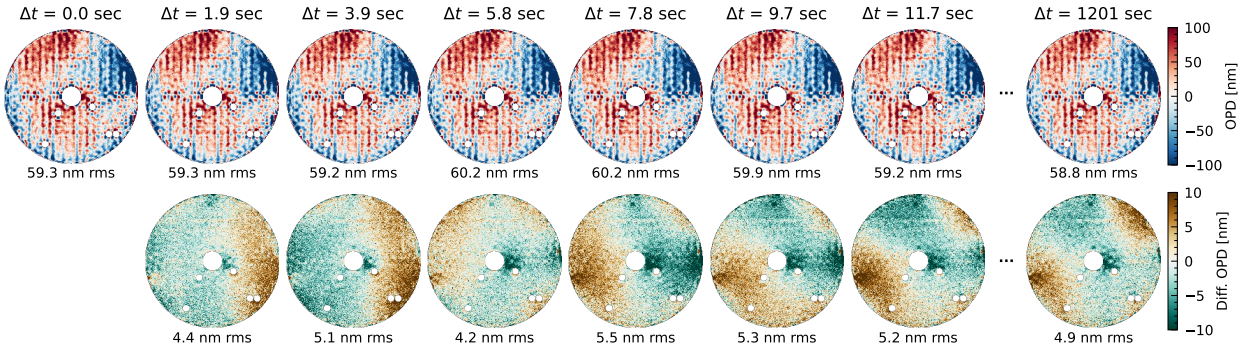



Figure 2: Example of ZWFS time series acquired in the ground-based VLT/SPHERE instrument over a period of several hours [10]. This unique type of data enables the determination of the temporal timescales involved in the decorrelation of wavefront errors as a function of spatial frequency, which is a critical parameter for very high contrast imaging. Similar measurements during a typical CGI observing sequence can tell us a lot about the behaviour of the instrument and of the whole observatory.

# References


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