Enhanced Wavefront Sensing for Roman CGI: Alternate Probes with Flight-Like Validation

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ROMAN SPACE TELESCOPE

THE ROMAN CORONAGRAPH AS A PATHFINDER FOR ACTIVE STARLIGHT SUPPRESSION WITH HWO

The Roman Coronagraph will perform **the first space-based demonstration of dark holes (DH)** - high-contrast detection zones in the image plane.
As the **last such mission before HWO**, it serves as a **key demonstrator for high-contrast imaging (HCI) technologies**.
Roman will use two deformable mirrors (DMs) to help the **coronagraph suppress on-axis starlight via active wavefront sensing and control** (WFS&C). This iterative process estimates the image-plane electric field, then computes DM commands to improve contrast. For Roman, raw data is downlinked to Earth for estimation and control, making it a **ground-in-the-loop (GITL) system**. This was validated in thermal vacuum (TVAC) tests using the required **near-field of view (NFOV) Hybrid Lyot Coronagraph (HLC)** mode.

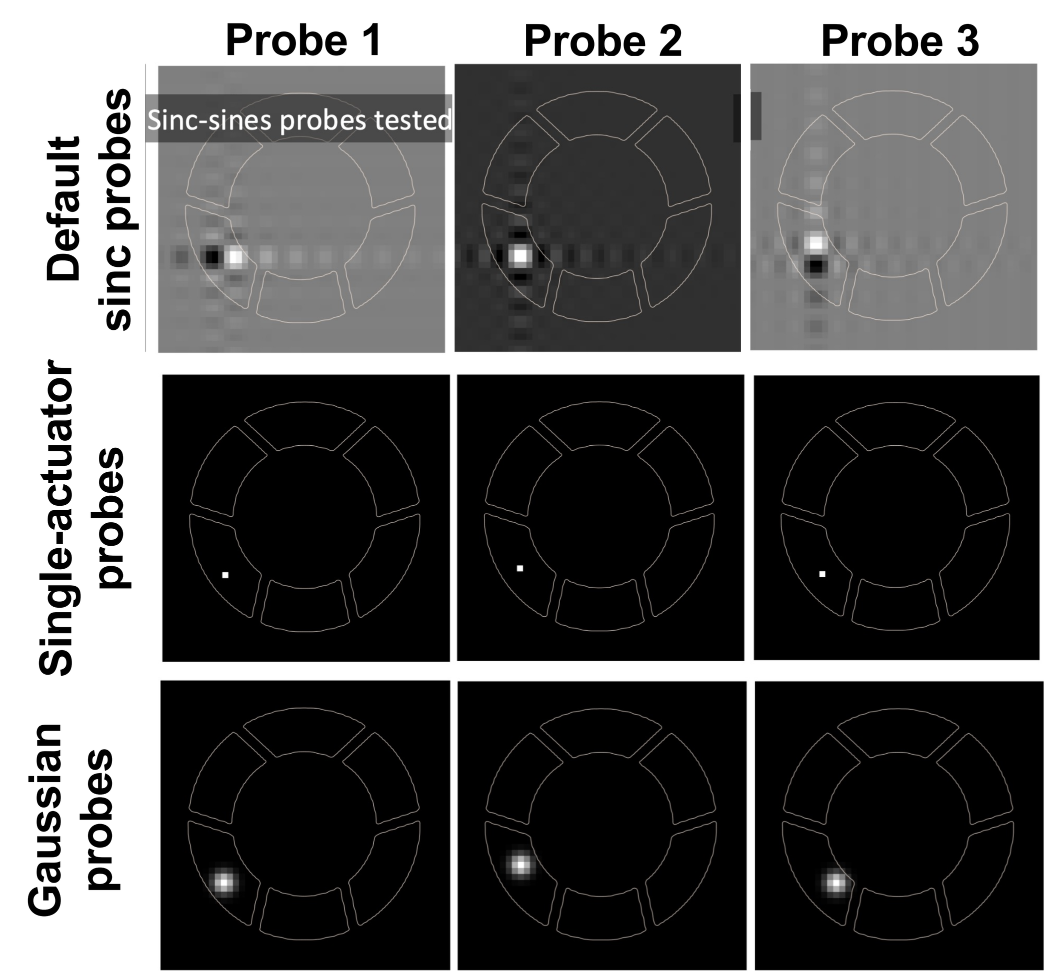
WAVEFRONT SENSING ON ROMAN: PAIR-WISE (PW) ESTIMATION

- Apply DM commands called "**probes**" to **introduce diversity.**
- Pairs of +/- application of applied probes allow **estimation of current electric field** in the image plane.
- The **baseline** probes on Roman are **sinc-sinc-sine probes**, modulating the phase diversity through **different probe shapes across a set of probes**.

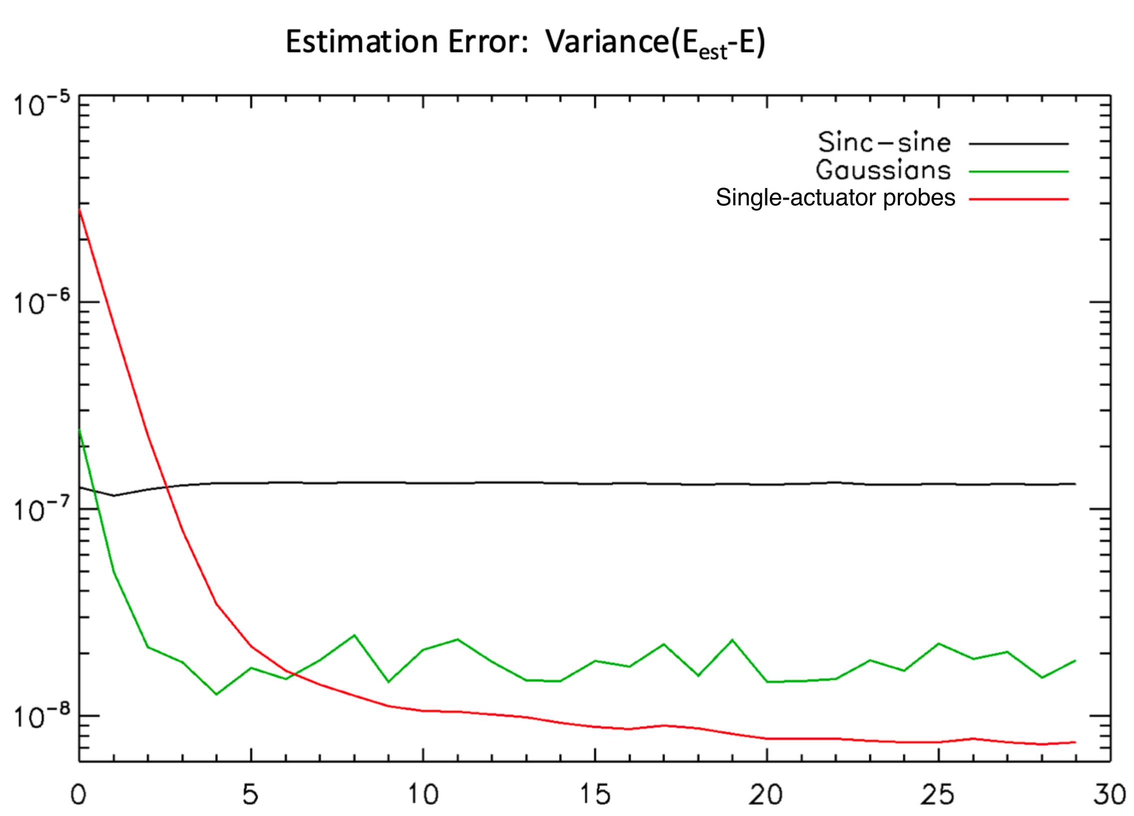
We report on the progress of **refining alternate probes to improve WFS&C loops.**
Testing alternate probes has been **prioritized for Roman CGI early observations (TD1).**

PROBING THE E-FIELD WITH ALTERNATE PROBES

- An alternative way to introduce phase diversity within a probe set is using the **same probe shape across the set**, with modulation through phase tilt in the image plane, which is achieved by **moving the location of a probe on the DM.**
- Simplest case: **single-actuator probes (SAP)**.
- The sinc probe unmodulated by sine (probe 2) still performs better than actuators, see below.
- → Create probe set from shifting sinc probe 2 like SAP.
- Probe shape can be simplified with **Gaussians probes.**
- Gaussians provide sufficient phase diversity while actuating fewer actuators than sincs and providing better **resilience to DM calibration errors and unknowns.**



ALTERNATE PROBES REDUCE ESTIMATION ERROR AT LATER ITERATIONS

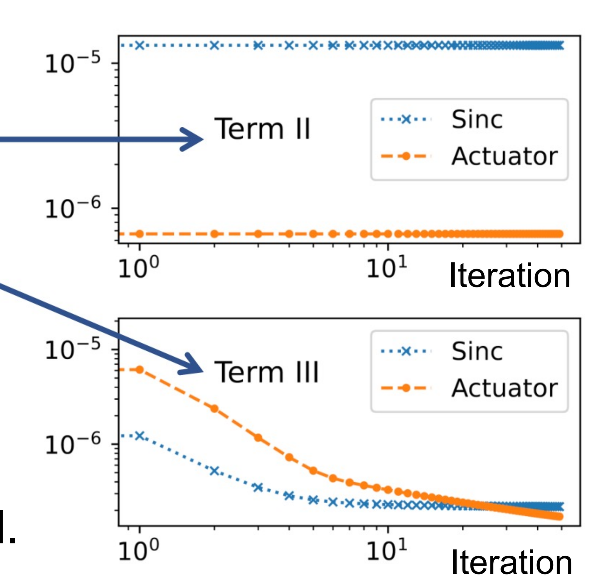


Numerical simulations show that the error on the E-field estimation is constant for sinc probes, while it drops to better levels for SAP and Gaussian probes as the DH contrast improves during iterations.

Linear expansion fo intensity difference in PW estimation:

$$\text{Frac error} = \frac{\text{std}(\Delta I_{\text{im},j} - 4\,\Re\{i E_{\text{im}} C\{E_{\text{pup}}\Psi_j\}^*\})}{\text{std}(4\,\Re\{i E_{\text{im}} C\{E_{\text{pup}}\Psi_j\}^*\})}$$

$$\begin{aligned}\Delta I_{\text{im},j} \simeq\ & 4\,\Re\left\{i\,E_{\text{im}}\,C\{E_{\text{pup}}\,\Psi_j\}^*\right\} \\ & - 2\,\Re\left\{i\,C\{E_{\text{pup}}\,\Psi_j\}\,C\{E_{\text{pup}}\,\Psi_j^2\}^*\right\} \quad (2) \\ & - \frac{2}{3}\,\Re\left\{i\,E_{\text{im}}\,C\{E_{\text{pup}}\,\Psi_j^3\}^*\right\} \quad (3) \\ & + \frac{1}{3}\,\Re\left\{i\,C\{E_{\text{pup}}\,\Psi_j^2\}\,C\{E_{\text{pup}}\,\Psi_j^3\}^*\right\} \\ & + \frac{1}{6}\,\Re\left\{i\,C\{E_{\text{pup}}\,\Psi_j\}\,C\{E_{\text{pup}}\,\Psi_j^4\}^*\right\}.\end{aligned}$$

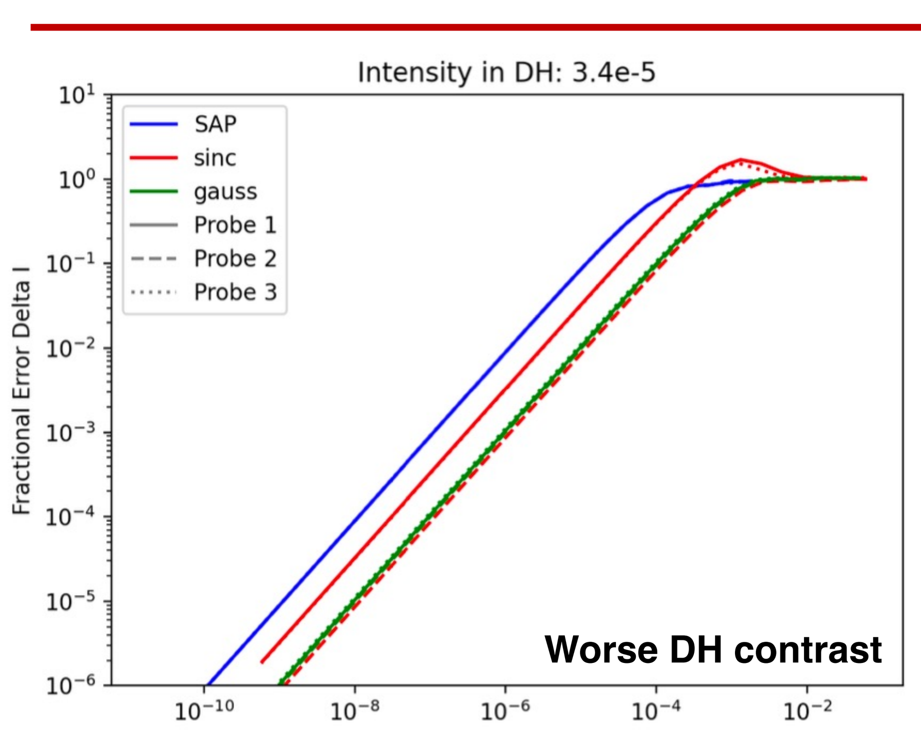


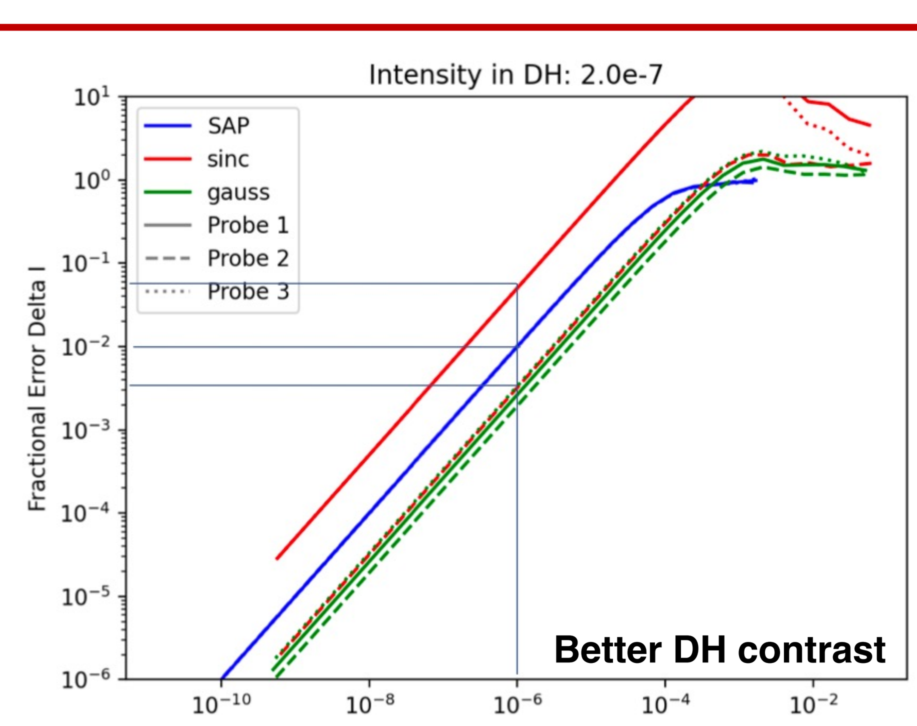
At fixed probe amplitude (Laginja et al. 2025):

- Term 3 decreases as contrast improves, for all probes.
- Term 2 remains constant, and is higher for sinc than for single-actuator probes.
- At a fixed contrast, term 3 is higher for single-actuator than for sinc probes.

When the contrast in the DH improves, nonlinear term 2 dominates w.r.t term 3, and the fractional error ΔI increases for a constant probe intensity.

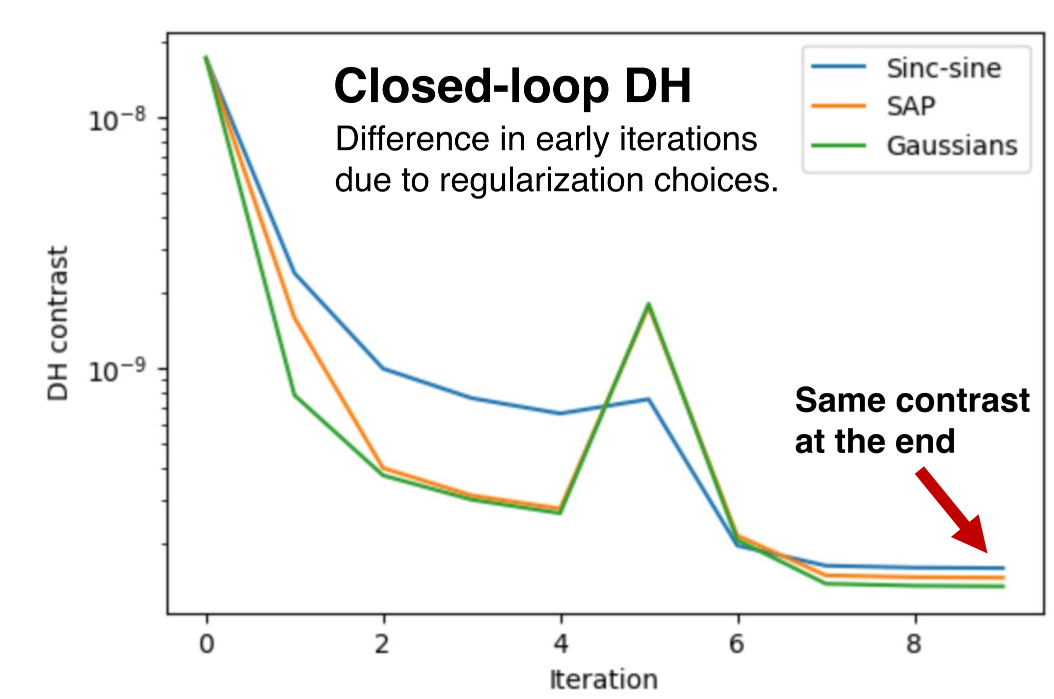
PROBE SHAPE INFLUENCES FRACTIONAL ERROR OF ESTIMATE





- At bad DH contrast (*left panel*), sinc probes are best.
- Below contrast of ~1e-6 (*right panel*), term 2 dominates for sincs and SAP. 2/3 sinc probes are worse than SAP.
- The best sinc probe is probe 2, not modulated by a sine → similar shape to Gaussian.
- Gaussian probes outperform the others in any case, for any DH contrast.

SIMULATIONS WITH CGI FLIGHT SOFTWARE: cgi-howfsc



- We compared closed-loop DH creation with different probes with the CGI flight software.
- All three types of probes allow to reach the same contrast floor in closed-loop WFS&C.

While sinc probes offer theoretical advantages through uniform DH modulation, **Gaussian probes confine DM perturbations to a small number of actuators**. This key benefit lies beyond current model predictions due to **poorly understood DM nonlinearities**, making alternative probing strategies essential to test in flight.

- General optimization of clipping on the incoherent background and on the regularization is required.

Preference to be given to probes with **lower nonlinearities** at later iterations as **frames will be used for science** (e.g. coherent differential imaging).

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Laginja et al. (2025) A&A
Potier et al. (2020) A&A
Groff et al. (2016) JATIS
Cady et al., (2025) JATIS
Riggs et al. (2025) *JATIS*
Krist et al. (2023) *JATIS*

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