The Gemini Planet Imager CAL2 upgrade, toward reflected light exoplanet imaging with high-speed focal plane wavefront sensing

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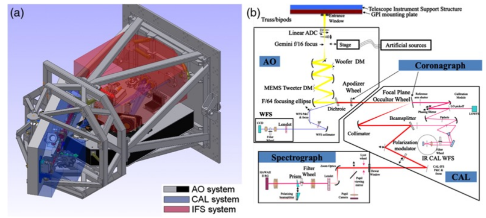
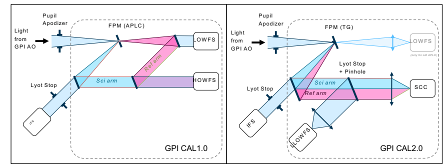
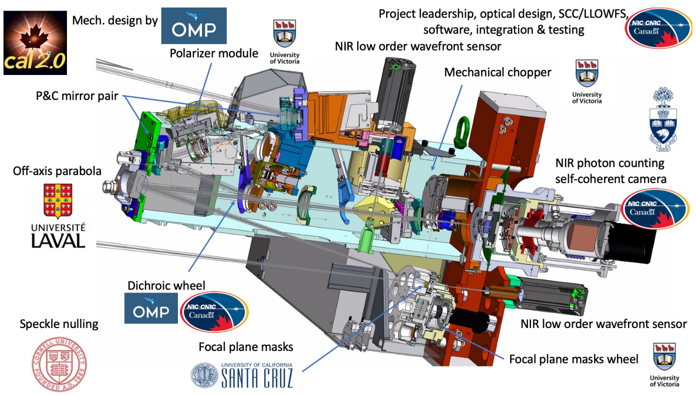
The search for exoplanets & debris disks using ground-based telescopes is currently limited by non-common path (NCPA) optical aberrations that generate quasi-static speckles in the coronagraphic focal plane, whose signal-to-noise ratio increases with integration time and can mask the faint exoplanet light. These speckles are evolving on a wide range of time scales and wavelengths that makes them difficult to calibrate and subtract by various post-processing approaches, such as reference/angular/spectral differential imaging. The National Research Council of Canada has developed a new "CAL" (calibration unit) system for the Gemini Planet Imager 2 (GPI2) instrument based on the self-coherent camera/FAST concept. The system is designed with a near-infrared photon counting camera capable of performing focal plane electric field measurements up to 200Hz, allowing for unprecedented active NCPA speckle corrections, while also enabling high-speed post-processing using the coherent differential imaging technique. CAL2 is expected to dramatically increase GPI2's sensitivity to fainter/lower mass exoplanets at small angular separations, especially on bright stars. I will describe CAL2's final optical/mechanical designs, and show pictures/results of its assembly/testing phases (Fall 2025). The CAL2 instrument integration in GPI2 is planned for early 2026, while first on-sky tests at the Gemini North observatory are expected Fall 2026.



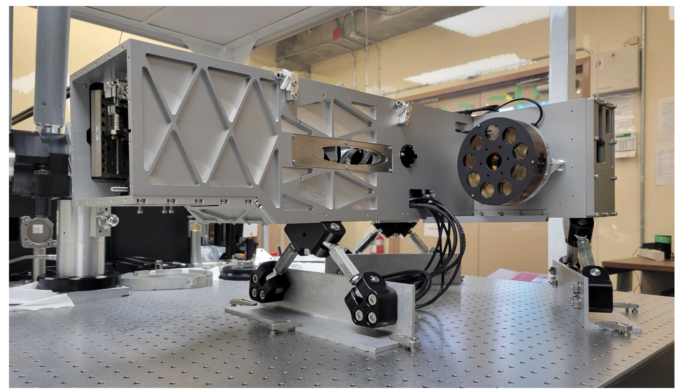
The Gemini Planet Imager (GPI)[1] Calibration (CAL)[2] system (blue box) hosts the instrument focal plane mask (FPM) wheel, the low-order wavefront sensor (LOWFS) for correcting slow beam drifts on the FPM, the non-common-path aberration (NCPA) corrector (high-order wavefront sensor; HOWFS loop), and a deployable polarization module. The CAL system relays the beam to the integral field spectrograph (IFS; red box) using two point-and-centering mirrors. Due to FPM vibrations and other issues, the original CAL HOWFS did not perform as expected and was never operated on sky.



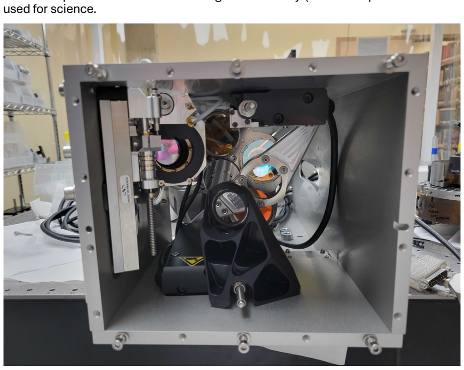
The original CAL HOWFS was a non-common-path pupil-plane interferometer. In CAL2[3], this has been replaced by a common-path focal-plane interferometer, which is far more robust against vibrations and flexure. The new design is based on the Self-Coherent Camera (SCC)[4] concept. A specialized focal plane mask (FAST)[5] reflects a fraction of the stellar diffraction core off-axis to create a reference beam. This beam is spatially filtered at the Lyot stop plane and recombined with the science beam in the focal plane, where it produces interference fringes (analogous to a double-slit experiment). Only coherent stellar light is fringed. These fringes are used in closed loop for focal-plane WFS and for coherent differential imaging[6].



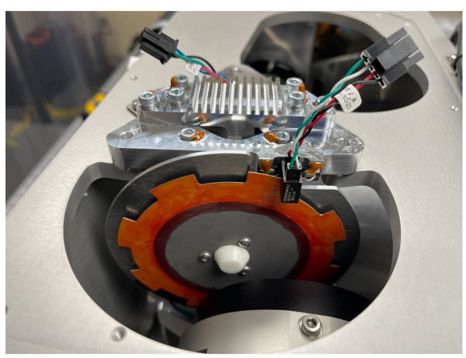
CAL2 is an internally funded National Research Council of Canada (NRC) project and an international collaboration involving four universities, OMP (Québec mechanical design), and NRC Herzberg Astronomy and Astrophysics. Light from the GPI adaptive optics system first encounters the FPM wheel, then a new off-axis parabola (OAP) and dichroic wheel. Reflected light is sent to a pair of point-and-centering mirrors, the deployable polarization module, and the IFS. Transmitted light passes through the dichroic to a reflective Lyot stop. The reflected component is used for a Lyot based LOWFS (First Light CRED2), while the transmitter light goes to an optical chopper, filter wheel, and imaging camera. The optical chopper "blinks" the SCC reference beam on and off, enabling fast, low-latency, and robust extraction of the interference fringes. The main SCC detector is a custom SAPHIRA 512×512 near-infrared photon-counting camera. Using a daytime interaction matrix, CAL2 aims to close the NCPA SCC loop at ~50 Hz and generate a dark hole for the IFS. The SCC operates with 1.5% bandpass filters to minimize fringe chromaticity (1.5% bandpass extracted from the FTS 20% bandpass). SCC images may also be used for science.



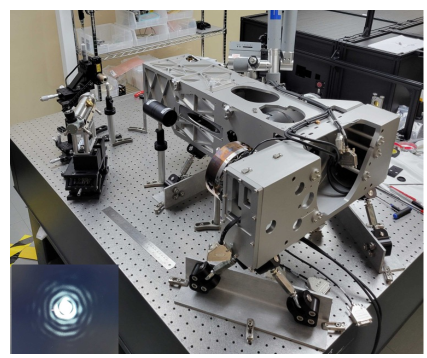
CAL2 has been fully fabricated and assembled at the NRC HAA NEW EARTH Laboratory. All mechanisms have been warm- and cold-tested and meet operational requirements. The FAST SCC focal plane masks were fabricated by Zeiss. CAL2 also supports legacy focal plane masks with the original LOWFS (First Light CRED2). New legacy FPMs were fabricated by SFU 4D Labs (Vancouver, Canada).



CAL2 internal view from the OAP. The polarization module is located top and left. A black baffle is seen at the front to block the reference beam light for the IFS path. The dichroic wheel is visible at the back. The diagonal structure with a circular aperture is a supporting beam.



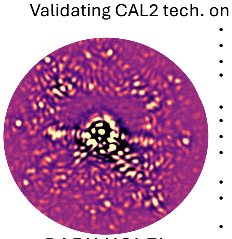
The CAL2 optical chopper operates from 0.1 to 200 Hz and stationary block/unblock mode to blink the SCC reference beam to acquire fringed and unfringed images in sequence. A simple image difference isolates the fringe signal for focal-plane wavefront sensing and coherent differential imaging. The chopper also serves as the system timing reference, synchronizing the SAPHIRA SCC camera (with pixel-level fringe flags) and the Lyot LOWFS CRED2. The legacy LOWFS, operating at ~1 Hz, is not synchronized and provides asynchronous drift offsets to the real-time computer.



CAL2 is currently undergoing final optical alignment and testing. The IFS path has been aligned, and the SCC path is now being aligned and tested. Final integration and tuning will occur once CAL2 is installed in GPI2, providing access to the deformable mirror for final focus and Lyot stop clocking.

Lower left panel: first light through the IFS path!

Validating CAL2 tech. on sky at Subaru with SPIDERS!



DARK HOLE!

- Regulus
- 60s integrated exposure
- 0.8-1.2" seeing with 40m/s wind
- Day time/internal light source interaction matrix
- Dark hole digging ~1min with low gains
- 1KHz LLOWFS ML (see Fogal et al. poster!)
- SCC loop stable for 30+ minutes
- Some challenges with CDI on sky (see Hessel et al. talk!)
- iFTS early results (see Johnson et al. poster!)
- For overall results, see Thompson et al. poster!
- See Marois et al. talk Friday for using SPIDERS for HWO R&D!

GPI2/CAL2 Timeline

- CAL2 Complete optical alignment & testing by end of February 2026
- CAL2 Team going to Notre-Dame for preparation work (late February 2026)
- Arrival of CAL2 at Notre-Dame (early March 2026)
- Complete CAL2 integration (by end of March 2026)
- CAL2 Software integration work (until end of 2026)
- GPI2/CAL2 shipping to Gemini North & on sky commissioning (early 2027 - depending on NSF funding)

CAL2 capabilities deployment phases

1. CAL2 behaving as the legacy CAL system (2026)
2. CAL2 new FPMs, LLOWFS control, and SCC CDI post-processing (by mid 2027)
3. CAL2 HOWFS SCC RTC loop integration (by mid 2028)

References

[1]Macintosh, B., Graham, J. R., Ingraham, P., et al., *"First light of the Gemini Planet Imager", Proceedings of the National Academy of Science, 111, 12661 (2014).*

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[4]Baudoz, P., Boccaletti, A., Baudrand, J., et al., *"The Self-Coherent Camera: a new tool for planet detection", IAU Colloq. 200: Direct Imaging of Exoplanets: Science & Techniques, 553 (2006).*

[5]Gerard, B. L., Marois, C., & Galicher, R., *"Fast Coherent Differential Imaging on Ground-based Telescopes Using the Self-coherent Camera", Astronomical Journal, 156, 3, 106 (2018).*

[6]Mann C. et al, *"Coherent Differential Imaging: squeezing Additional Imaging Contrast Behind the Self-Coherent Camera on SPIDERS", Proc. SPIE 13097-239 (2024).*