Invited Paper

Upgrading the Gemini Planet Imager to GPI 2.0

Saavidra Perera[a], Jeffrey Chilcote[b], Quinn Konopacky[a], Joeleff Fitzsimmons[c], Randall Hamper[b], Bruce Macintosh[d], Christian Marois[c,e], Dmitry Savransky[f], Remi Soummer[g], Jean-Pierre Veran[c], Guido Agapito[h], Arlene Aleman[d], S. Mark Ammons[i], Marco Bonaglia[h], Marc-Andre Boucher[j], Joel Burke[b], Maeve Curliss[k], Robert J. De Rosa[l], Clarissa Do Ó[a], Jennifer Dunn[c], Simone Esposito[h], Guillaume Filion[j], Dan Kerley[c], Jean-Thomas Landry[j], Olivier Lardiere[c], Daniel Levinstein[a], Duan Li[f], Mary Anne Limbach[k], Alex Madurowicz[d], Jérôme Maire[a], Maxwell Millar-Blanchaer[m], Bryony Nickson[g], Eric L. Nielsen[n], Jayke Nguyen[a], Meiji Nguyen[g], Dillon Peng[b], Marshall D. Perrin[g], Emiel Por[g], Lisa Poyneer[i], Laurent Pueyo[g], Fredrik Rantakyrö[o], Brian Sands[b], Eckhart Spalding[b], and Kaitlyn Summey[f]

[a]Center for Astrophysics and Space Science, University of California San Diego, La Jolla, CA 92093, USA
[b]Department of Physics, University of Notre Dame, 225 Nieuwland Science Hall, Notre Dame, IN 46556, USA
[c]National Research Council of Canada Herzberg, 5071 West Saanich Rd, Victoria, BC, V9E 2E7, Canada
[d]Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94305, USA
[e]University of Victoria, 3800 Finnerty Road, Victoria, BC, V8P 5C2, Canada
[f]Sibley School of Mechanical and Aerospace Engineering, Cornell University, Ithaca, NY 14853, USA
[g]Space Telescope Science Institute, Baltimore, MD 21218, USA
[h]INAF - Arcetri Observatory, Largo Enrico Fermi 5, 50125 Florence, Italy
[i]Lawrence Livermore National Laboratory, Livermore, CA 94551, USA
[j]146 Bigaouette St. Quebec City, QC, Canada, G1K 4L2
[k]Department of Physics and Astronomy, Texas A&M University, 4242 TAMU, College Station, TX 77843-4242 USA
[l]European Southern Observatory, Alonso de C'ordova 3107, Vitacura, Santiago, Chile
[m]Univ. of California, Santa Barbara, Santa Barbara CA 93106
[n]Department of Astronomy, New Mexico State University, 1320 Frenger Mall, Las Cruces, NM 88003, USA
[o]Gemini Observatory, 670 N. A'ohoku Place, Hilo, HI 96720, USA

ABSTRACT

The Gemini Planet Imager (GPI) is a high-contrast imaging instrument designed to directly detect and characterize young, Jupiter-mass exoplanets. After six years of operation at Gemini South in Chile, the instrument is being upgraded and relocated to Gemini North in Hawaii as GPI 2.0. GPI helped establish that Jovian-mass planets have a higher occurrence rate at smaller separations, motivating several sub-system upgrades to obtain deeper contrasts (up to 20 times improvement to the current limit), particularly at small inner working angles. This enables access to additional science areas for GPI 2.0, including low-mass stars, young nearby stars, solar system objects, planet formation in disks, and planet variability. The necessary instrumental changes required to

Further author information: (Send correspondence to Saavidra Perera)
Saavidra Perera: E-mail: sperera@ucsd.edu

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enable these new scientific goals are to (i) the adaptive optics system, by replacing the current Shack-Hartmann wavefront sensor (WFS) with a pyramid WFS and a custom EMCCD, (ii) the integral field spectrograph, by employing a new set of prisms to enable an additional broadband (Y-K band) low spectral resolution mode, as well as replacing the pupil viewer camera with a faster, lower noise C-RED2 camera (iii) the calibration interferometer, by upgrading the low-order WFS used for internal alignment and on-sky target tracking with a C-RED2 camera and replacing the calibration high-order WFS used for measuring and correcting non-common path aberrations with a self coherent camera, (iv) the apodized-pupil Lyot coronagraph designs and (v) the software, to enable high-efficiency queue operations at Gemini North. GPI 2.0 is expected to go on-sky in early 2024. Here I will present the new scientific goals, the key upgrades, the current status and the latest timeline for operations.

Keywords: Direct Imaging; High Contrast Imaging; Adaptive Optics; Extrasolar Planets; Coronagraphy; Integral Field Spectrograph

1. INTRODUCTION

The Gemini Planet Imager (GPI) is a facility-class instrument that was designed to directly image and characterise young Jupiter-mass exoplanets and search for circumstellar debris disks that are sculpted by planetary systems. The instrument was designed to operate at either Gemini North or Gemini South Telescopes and was installed at Gemini South, Chile, in 2013. It was fully operational for general science cases from 2014 until 2020 when it was decommissioned. The instrument made a number of key scientific observations, including the discovery of 51 Eri b and HR 2562 b.[1,2] GPI consisted of five major hardware subsystems: an adaptive optics (AO) system, an apodized-pupil Lyot coronagraph (APLC), a precision infrared wavefront sensor (CAL), a near-IR integral field spectrograph (IFS) and an optomechanical subsystem to hold all of the components together (OMSS). Additionally, software components included a top-level computer (TLC) and a data reduction pipeline (DRP), written in IDL, to reconstruct raw IFS images into three-dimensional data cubes and provide basic PSF subtraction.

GPI was reviewed for a possible relocation from Gemini South to Gemini North in 2018.[3,4] Since relocation would require significant disassembly of the instrument, it was recommended that the instrument undergo major servicing. This also provided an ideal opportunity to implement hardware upgrades to access the next generation of science requirements. This upgraded GPI instrument is referred to as GPI 2.0.

In this paper, we will present the new science goals for GPI 2.0 in section 2, along with the necessary subsystem requirements to realise these goals. In section 3 we will outline how the hardware upgrades will enable these subsystem requirements. Finally, the current status of the upgrade as well as the projected timeline will be outlined in section 4.

2. SCIENCE GOALS

GPI aimed to describe the distribution of young Jupiter mass planets on wide orbits (> 10 AU). Results from GPI, and other large-scale surveys, indicate that the peak occurrence is between the 3-10 AU.[5] Therefore, GPI 2.0 aims to further describe this distribution of these planets by accessing smaller inner working angles (IWAs) at deeper contrasts. In addition to this primary goal, a series of science cases, detailed in Ref. 6, were evaluated in 2017 and 2018 as part of a process to decide on the hardware upgrades required for GPI 2.0. Requirements for hardware upgrades were derived from several proposed science cases. The key identified science areas were low-mass stars, young nearby stars, solar system objects, planet formation in disks, and planet variability. Table 1 shows the required improvement in WFS I-band magnitude, IWA and contrast magnitude for each of the proposed science cases.

The original GPI operated at a WFS $I = 9$. By pushing this to $I = 14$ we will be able to access observations such as nearby AGN and solar system objects. Most notably the contrast improvement of 2+ magnitude will open the door to observations of cold-start planets as illustrated by figure 1. GPI 2.0 aims to differentiate between the two canonical planet formation processes; the low-entropy "cold-start" models[7] and the high-entropy "hot-start" models.[8] Figure 1 shows that with a 3.2 magnitude contrast improvement, GPI 2.0 would be able to increase the yield of cold-start planets by a factor of 10.

Table 1. New science objectives for GPI 2.0 and the necessary WFS magnitude, inner working angle and contrast improvement.

Science Goals	WFS I-magnitude	Inner working Angle	Contrast Improvements
Large-scale survey / cold-start planets	10	0.15”	2+ mag
Very young stars + transitional disks	13	0.1”	0
Asteroids & solar system objects	13-14	-	0
Debris Disks	9	0.2”	0
Planet Variability & abundance characterisation	6	0.2”	1% photometry high-res
Evolved Stars	9	0.1”	0
Nearby AGN	14	-	Only modest contrast required

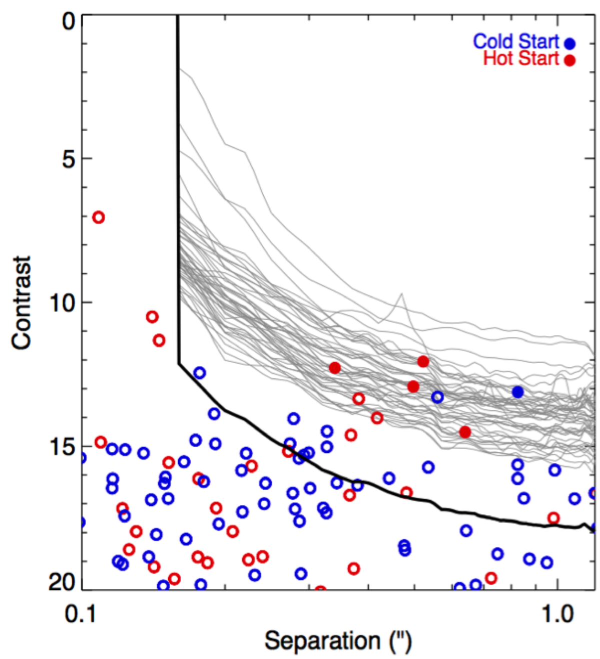

Figure 1. Simulation of the distribution of hot (red) and cold (blue) start planets as a function of contrast magnitude and separation. The grey lines show examples of typical contrast curves obtained with the original GPI and the black line illustrates a contrast improvement of 3.2 magnitude.[9]

3. UPGRADES

In order to reach fainter WFS targets and smaller IWAs at deeper contrasts, a number of hardware and software upgrades are required. Figure 2 highlights the key subsystem upgrades for GPI 2.0 and how it compares to the original GPI instrument. This section will briefly describe the upgrades to the individual subsystems.

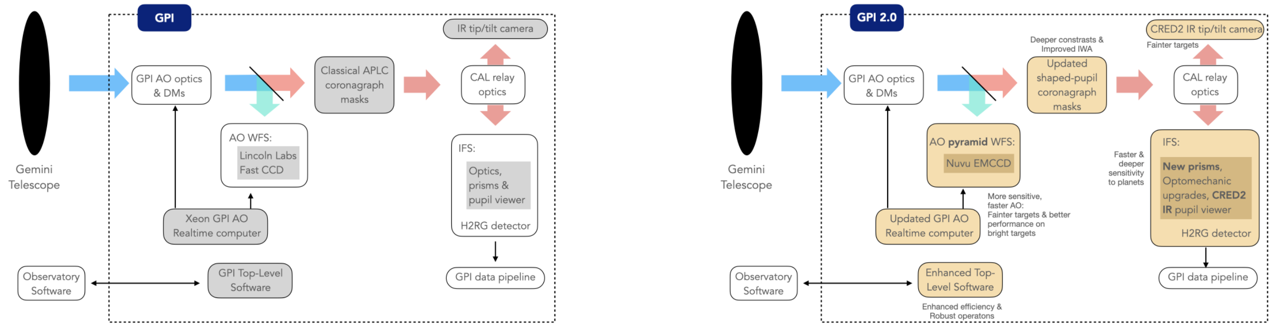

Figure 2. Schematic of key components of GPI (left) and GPI 2.0 (right). The highlighted subsystems in GPI 2.0 indicate where upgrades are taking place.

3.1 Adaptive Optics

The original GPI AO system utilised a Shack-Hartmann WFS (SHWFS) and a Lincoln Labs CCID-66 sensor, along with a CILAS 95-actuator piezoelectric deformable mirror (DM) and a Boston Micromachines 4096-actuator micro-electro-mechanical (MEMS) DM. This AO system reached a limiting magnitude of $I = 9$. As illustrated by Table 1 many of the GPI 2.0 science objectives require fainter magnitude, I = 13-14, targets. In order to reach this requirement the AO system is replacing the original SHWFS with a new pyramid wavefront sensor (PWFS). For a complete description of the PWFS design and test plan see Ref. 10 and Ref. 11 respectively. Figure 3 shows the layout of the PWFS bench highlighting its key components including a new EMCCD. The PWFS employs two fast steering mirrors; the modulation stage and tip/tilt stage. The modulation stage will modulate and dither the focused spot around the tip of the pyramid. The typical radius of the modulation circle, produced by FSM1, will be $3\lambda/D$ and must evenly illuminate the four quadrants of the pyramid. The EMCCD is a Nüvü custom camera with near-zero noise, high quantum efficiency and fast readout, and will operate at frequencies up to 2 kHz (though capable of 3 kHz). For a thorough evaluation and characterisation of the EMCCD see Ref. 12. The PWFS bench is complete with baffling and a field stop to reduce background noise and source confusion. Figure 4 shows an image of the PWFS bench with all optical components at UC San Diego.

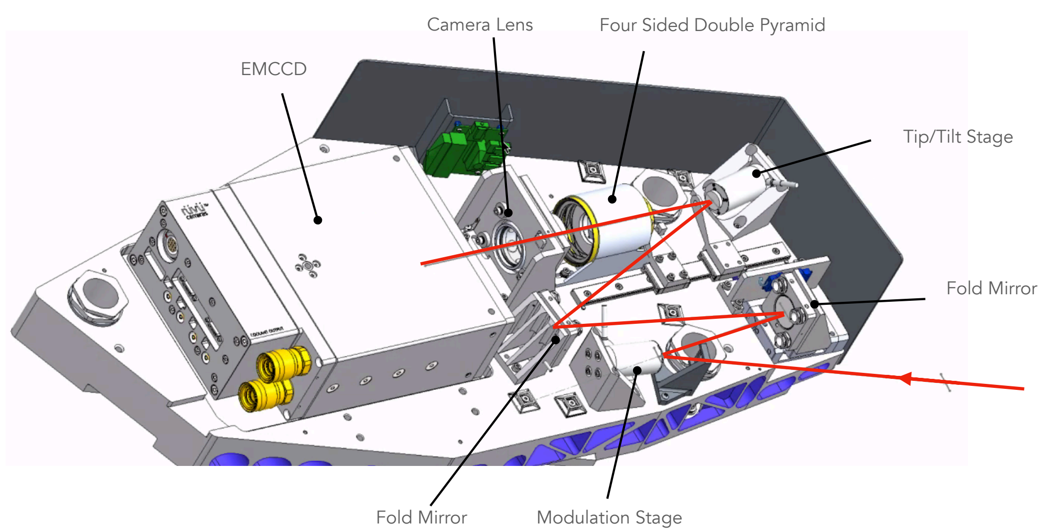

Figure 3. AutoCAD drawing of the PWFS bench, with the light path illustrated by the red line.

In addition, the current real-time controller software will be updated to the Herzberg Extensible Adaptive Real-time Toolkit (HEART).[13] The original GPI WFS required 2.3 ms from the start of acquisition to the end of the readout. HEART will allow GPI 2.0 to reduce this time to 1.1 ms. A faster AO system results in more stable observations on brighter targets.

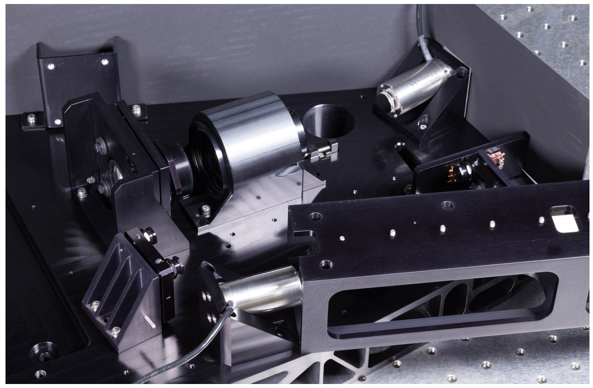

Figure 4. Image of the PWFS bench with laser jig in the laboratory.

3.2 Coronagraphic Subsystem

In order to reach GPI 2.0's aims to obtain deeper contrasts at smaller inner working angles and improve the performance of fainter targets, a new generation of APLC masks has been designed.[14,15] Since the conception of the original GPI coronagraph design ($\sim$ 2008),[14,15] APLC design has advanced to work with binary, shaped-pupil apodizations generated by full numerical optimization.[16–18] This upgrade takes advantage of a decade of technology and concept development since the original GPI coronagraphs were designed. GPI 2.0 will pair new pupil plane masks and lyot stops, with the original GPI focal plane masks. The new apodizer and lyot mask combinations have been designed by Russel B. Makidon Optics Laboratory at the Space Telescope Science Institute.[19] Eight new apodisers have been procured and optimised for throughput and contrast. For example, a new H band apodiser for a H band focal plane mask will achieve $\sim 10^{-7}$ contrast at an IWA of 125 mas, compared to the $\sim 10^{-5}$ at the same IWA. Figure 5 shows an example lyot stop and apodisers.

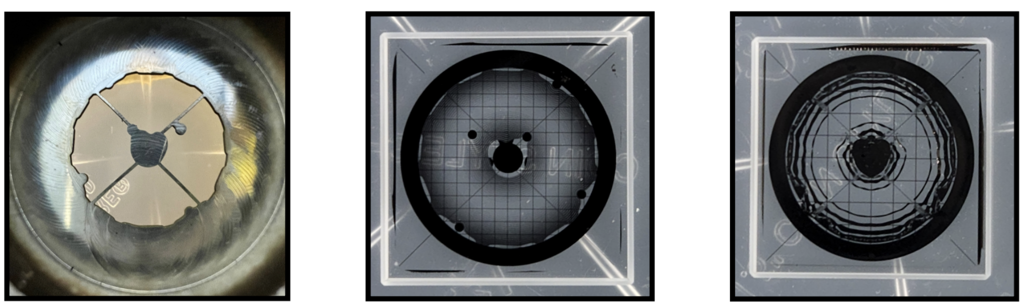

Figure 5. Example Lyot stop (left) and apodisers (middle, right)

3.3 Calibration Unit

The CAL was employed to tackle non-common path aberrations (NCPAs). It consisted of a low-order WFS (LOWFS) and a high-order WFS (HOWFS). The upgrade of the CAL will take place in two phases. Phase one (CAL 1.1) will upgrade the LOWFS by employing First Light's CRED-2 camera. This will improve the operable range to fainter stars of an H-mag of 12.[20] In addition, a Zernike WFS will be added to further tackle the NCPAs, as described by Ref. 21. In the original GPI instrument, the HOWFS utilised a dual-arm interferometer design and did not work on-sky due to vibrations. Therefore phase two (CAL 2.0) will upgrade HOWFS by employing a self-coherent camera (SCC) that uses a common-path interferometer design to enable focal plane wavefront sensing and control. The design and overview of CAL 2.0 is discussed in depth in Ref. 22–25. The final design review of CAL 2.0 is expected in early 2024, with lab testing taking place in the Summer.

3.4 Integral Field Spectrograph

The IFS is a cryogenic instrument sensitive from $0.95 - 2.4$ μm that measures an image at multiple wavelengths simultaneously.[26,27] GPI had a prism of resolving power of R=∼30-100 depending upon the band, and 5 individual filters; Y, J, H, and 2 in K-band (split into overlapping segments). The IFS additionally had a Wollaston prism to allow for polarization measurements but only in broad band, and will remain in GPI 2.0.[26,27]

As part of the GPI upgrade new prisms have been manufactured to enable a low-resolution observing mode, and a higher-resolution mode similar to the original GPI resolution but more even across the bands, as shown in Table 2. A combination of N-SF66 and CaF_2 was chosen for both low and high-resolution prisms.

The low-resolution mode will operate from the $Y-K$ band simultaneously, allowing for the search of new and fainter planets and thereby maximising observing efficiency. In addition, the broader spectral range will enable GPI to improve its photometric calibration between spectra. The high-resolution prism will enable observation of the full K band (2 - 2.4 μm). Since the original GPI prism split the K band into two "sub" bands, acquiring the full band required doubled the observation time. The new prism would therefore increase the efficiency of observation in this band. The design and detailed description of the expected performance of the prisms, along with the upgrade status of the IFS is outlined in Ref. 28.

Table 2. Low-resolution and high-resolution prism.

	Low-Res			**High-Res**		
Band	**Cut-on/off** (μm)	**Length (pix)**	$R = \lambda/\Delta\lambda$	**Cut-on/off** (μm)	**Length (pix)**	$R = \lambda/\Delta\lambda$
Y	0.95-1.07	2.7	13.6	0.95-1.07	14.7	61.9
J	1.17-1.33	2.7	10.5	1.13-1.34	17.5	47.9
H	1.49-1.78	3.4	9.6	1.498-1.796	15.4	42.7
K	2.00-2.40	4.5	12.4	2.00-2.40	20.0	55.1
Broad				0.97-2.40	20.0	11.8

4. CURRENT STATUS & CONCLUSION

In 2020B, GPI 1.0 was expected to be packed and shipped from Gemini South Telescope to the University of Notre Dame. However, due to COVID-19 and civil unrest in Chile, this was delayed by ∼2 years. In the Summer of 2022, GPI was finally ready to be shipped, and a series of pre- and post-shipping tests were performed to evaluate the instrument's condition.[29] These tests were part of the original construction of GPI 1.0 allowing the GPI consortium to maintain a long-term baseline and record of its performance. The approximate two-year delay has resulted in a delay in the upgrade schedule of similar length. GPI has been dissembled and prepared for the integration of the upgraded subsystems. All hardware has been procured and alignment has begun. The first integration will be the AO system, with the IFS being the last. Subsystem integration is expected to be completed in 2024A, and available for shipping in 2024B. Integration with the observatory is then expected to take six to nine months to complete with shared risk observations taking place at the end of the year. This indicates general science observations will begin in 2025A.

Since the design of GPI, 10+ years ago, many advancements in the field of extreme adaptive optics have been made. These advancements along with results from GPI and other large-scale surveys, have informed the necessary upgrades that need to be made to remain a competitive instrument.

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