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GPI 2.0: Baseline testing of the Gemini Planet Imager before the upgrade

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ABSTRACT

Over a period of about six years the Gemini Planet Imager instrument has carried out a host of adaptive-optics fed high-contrast imaging observations from the Gemini South telescope in Chile, including the successful GPIES exoplanet direct imaging survey. GPI will now be upgraded for increased sensitivity and science capabilities, and will perform a new exoplanet imaging survey from Gemini North telescope in Hawaii. The disassembly and reintegration of the instrument as GPI 2.0 will take place at the University of Notre Dame in Indiana, USA. Here we describe results of tests we have conducted remotely of the GPI instrument before shipment from Chile. These tests were originally designed for the first incarnation of the instrument to accommodate science program imperatives and to ensure seamless compatibility with the host observatory. We have now performed those tests anew wherever possible, so as to assess the state of the instrument following its years-long science campaign (during which the instrument was not re-tested). These tests serve to flag potential areas of concern as early as possible and to help track changes during the shipment process. These tests involve the performance of the optomechanics, the detectors, the coronagraph, and other aspects of the instrument's hardware and software. We present the high-level results of this baselining process, describe their implications and limitations, and compare them with results from tests performed when the original instrument was shipped to Chile in 2013.

Keywords: exoplanets, adaptive optics, infrared

1. INTRODUCTION

The Gemini Planet Imager (GPI) instrument was designed as a dedicated instrument for the direct imaging of exoplanets using an Apodized-Pupil Lyot Coronagraph (APLC) together with either an integral field spectroscopy mode in bands 1.0–2.5 μm, or a broadband polarimetric mode, downstream of an internal adaptive optics system. Installed at the Gemini South telescope on Cerro Pachón in Chile in 2013, GPI carried out the GPIES exoplanet survey and guest observer science observations until 2020. The instrument has imaged protoplanetary disks, debris disks, and uncovered one new planet, 51 Eri b. An interim meta-analysis of the GPIES survey has provided evidence for core accretion planet formation models, and for a correlation between host star masses and wide-orbit planet occurrence rates [1].

In 2019, the NSF awarded MRI grant funding to upgrade the instrument and move it to the Northern Hemisphere, to Gemini North on Mauna Kea. This upgrade will provide GPI 2.0 with a smaller inner working angle, an increase in sensitivity of ≈2 mag in H-band to stellar companions, and be able to control the wavefront around stars ≈3 mag dimmer, among other changes to the instrument. The primary science objective is to image planets with low-entropy ("cold") starts, a heretofore uncharted region of parameter space, which will place tighter constraints on formation models. The upgrade process is a multi-institutional effort, and will primarily take place at the University of Notre Dame in Indiana, USA. (For a high-level overview, see Chilcote

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et al. in these proceedings, and [2] and [3].) Hardware is also being designed or built at UC San Diego, CA; the Space Telescope Science Institute, MA; and the NRC-Herzberg Astronomy & Astrophysics, Canada.

In the years prior to its installation at Gemini South in 2013, a series of performance requirements were quantified to ensure that GPI met engineering requirements for the host telescope, and could fulfill the science requirements. A series of corresponding tests was designed to ensure the instrument met these benchmarks. These Functional and Performance Requirements (FPR) tests were performed in-situ at the University of California at Santa Cruz in the spring and summer 2013. GPI was shipped to Gemini South in August of that year, and integrated to the telescope in October.

Following years of science observations and the awarding of the NSF MRI grant in 2019, GPI science operations abruptly ended in March 2020 at the international onset of the COVID-19 pandemic. By that time, the instrument had not been characterized in $\approx$8 years. Before shipment to the U.S. for GPI 2.0, a subset of tests was re-performed remotely to see how the instrument had aged, identify any potential areas of concern, and to establish a baseline state of the instrument before the shipment process.

In the following, we describe the layout of the instrument and the components tested in Sec. 2, the tests as performed in 2013 at Santa Cruz in Sec. 3, and the tests as performed in 2021 before shipment from Chile in Sec. 4. In Sec. 5 we tabulate and compare the results, and we conclude in Sec. 6.

2. LAYOUT OF THE INSTRUMENT AND TEST DESIGN

The GPI instrument is split into three main subsystems. Fig. 1 shows a global schematic and physical exterior view of the instrument, wherein light from the telescope is funneled into an adaptive optics (AO) subsystem to remove atmospherically-induced wavefront aberrations; then proceeds into a calibration unit (CAL) to remove quasistatic aberrations; and then into the integral field spectrograph (IFS) science camera.

2.1 Subsystems

The AO system (Fig. 2) contains a "woofer" mirror on a stage to remove low-spatial-frequency aberrations; and a MEMS deformable mirror (DM) to remove higher-order aberrations [4]. A dichroic sends visible light to a Shack-Hartmann wavefront sensor, and passes infrared light through an apodizing element and into the CAL. The CAL (Fig. 3) splits light into a low-order wavefront sensor channel, and two other beams that are interferometrically recombined for a high-order wavefront sensor. Science light proceeds through a polarization modulator, exits the CAL, and enters the IFS. A phase-apodized-pupil Lyot coronagraph (APLC) to remove light from host stars has multiple elements which appear at planes in all three subsystems. Inside the IFS science camera (Fig. 4), the light passes through the final APLC element (a Lyot stop), and during science observations the light passes through a lenslet array and onto a HAWAII 2RG detector. (For details on subsystem upgrades for GPI 2.0, see Do Ó et al., J. Nguyen et al., M. Nguyen et al., Peng et al., and Perera et al., in these proceedings.)

GPI was opened a few times as part of commissioning in 2013, and only once again after 2014. In all the time the instrument has been sealed, there are various channels for inflicting wear on the system, including thermal and gravity vector cycles which can fatigue or dislocate metal components and optics; wearing of motor gears and electronics; rupture of hose cladding; changing mirror actuator responses; evaporation of optical coatings; accumulation of condensates from outgassing materials internal to the instrument, or vacuum leaks; failing artificial calibration light sources; loosening of screws and bolts; electrostatic discharges that can corrupt electronics; and many others.

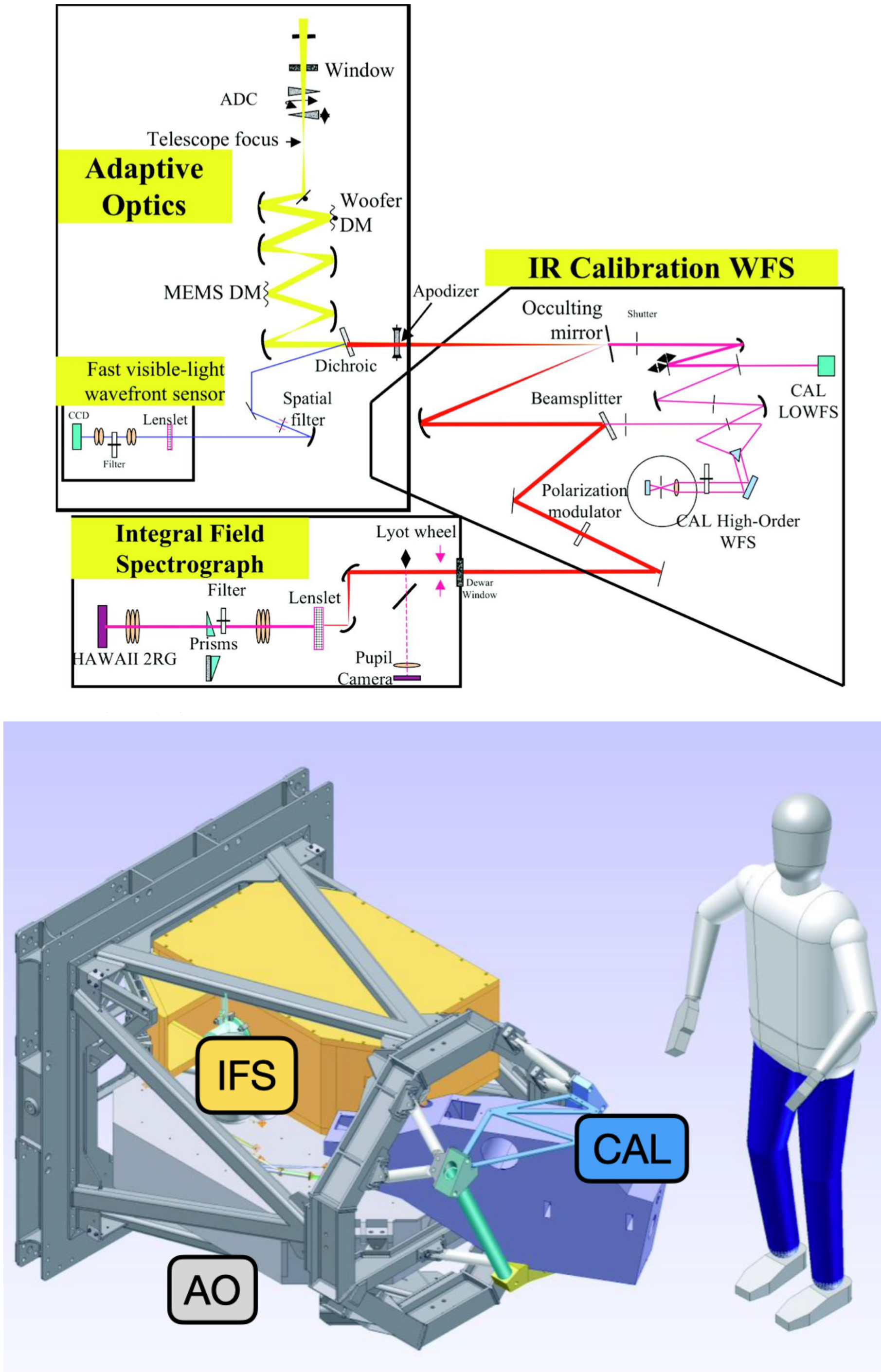

Figure 1: Top: Schematic of GPI 1.0. Bottom: A global view of GPI, showing the support structure, AO, IFS, and CAL.

2.2 Test Design

Some Functional and Performance Requirements (FPR) tests are of top-level, one-point-failure functionality that must be met for the instrument to operate at all (such as compatibility with the telescope optics and ports).

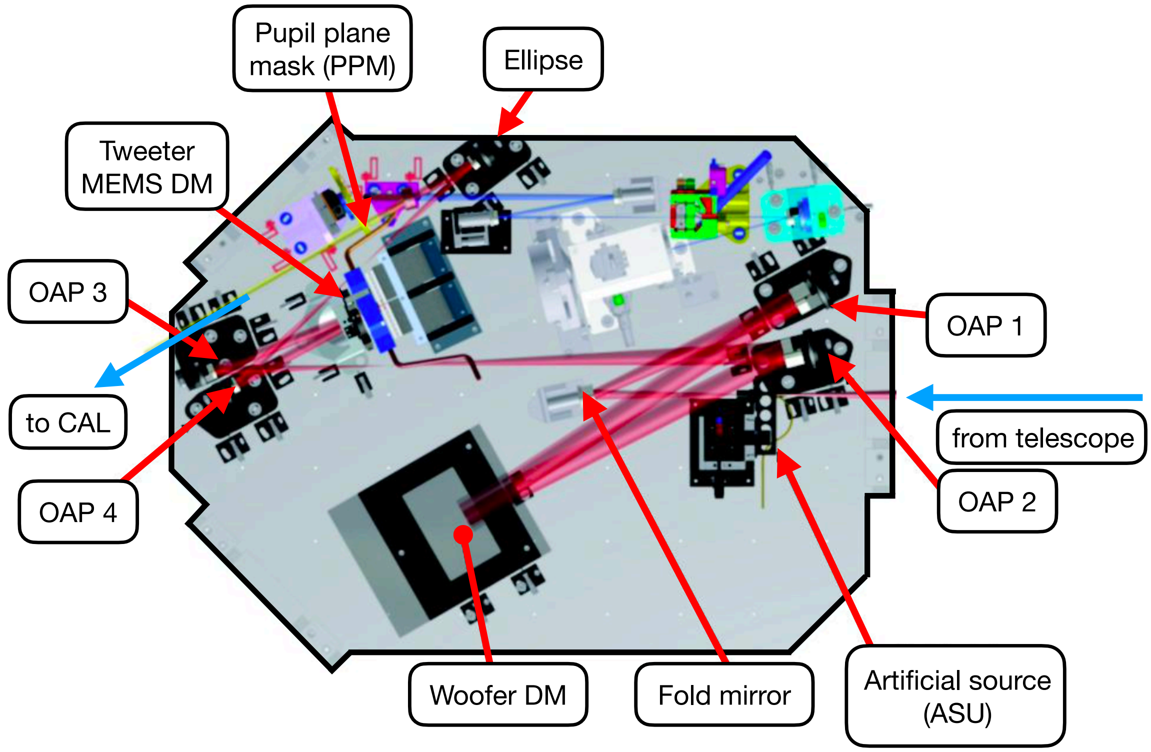

Figure 2: The GPI 1.0 AO relay bench.

Other FPR tests represent performance goals (such as achieved contrasts in the science frames), and a failure to meet a given performance metric can pose varying levels of impediment, depending on the amount of leeway available. Lower-level instrument tests serve as checkouts of different subsystems. Some are highly modular (such as the tilt cadence of a particular mirror) while others potentially contain the effects of many different parts of the instrument (such as collective mechanism configuration times).

3. TESTS IN 2013, PRE-SHIPMENT IN SANTA CRUZ

Tests were carried out in 2013 at UC Santa Cruz with GPI either sitting stationary or bolted to a flexure stand to reproduce gravity vector changes that would be expected on the telescope. (Other early testing of GPI is described in [7] and [8].)

A column in Table 1 shows the 2013 test results in PASS/FAIL format, with abbreviated descriptions of the tests. This boolean verdict can be misleading, as there may still be margin for performance changes. Failures in the 2013 tests (which were still relevant for GPI 2.0) were the following, listed by FPR number. No failures posed major problems.

- 140: Observing efficiency. The efficiency was 76% (short of a goal of 90%), because detector readout overheads had been underestimated.
- 180: Internal contrast ratio. Contrast was ∼3-4 times worse than required, but the data reduction has improved since then.
- 680: Pupil viewing mode (sensitivity only). Much longer exposures with the pupil-viewing engineering camera were necessary (12 sec to get S/N=5 on a given brightness, instead of the goal of 1 sec to obtain S/N=1).

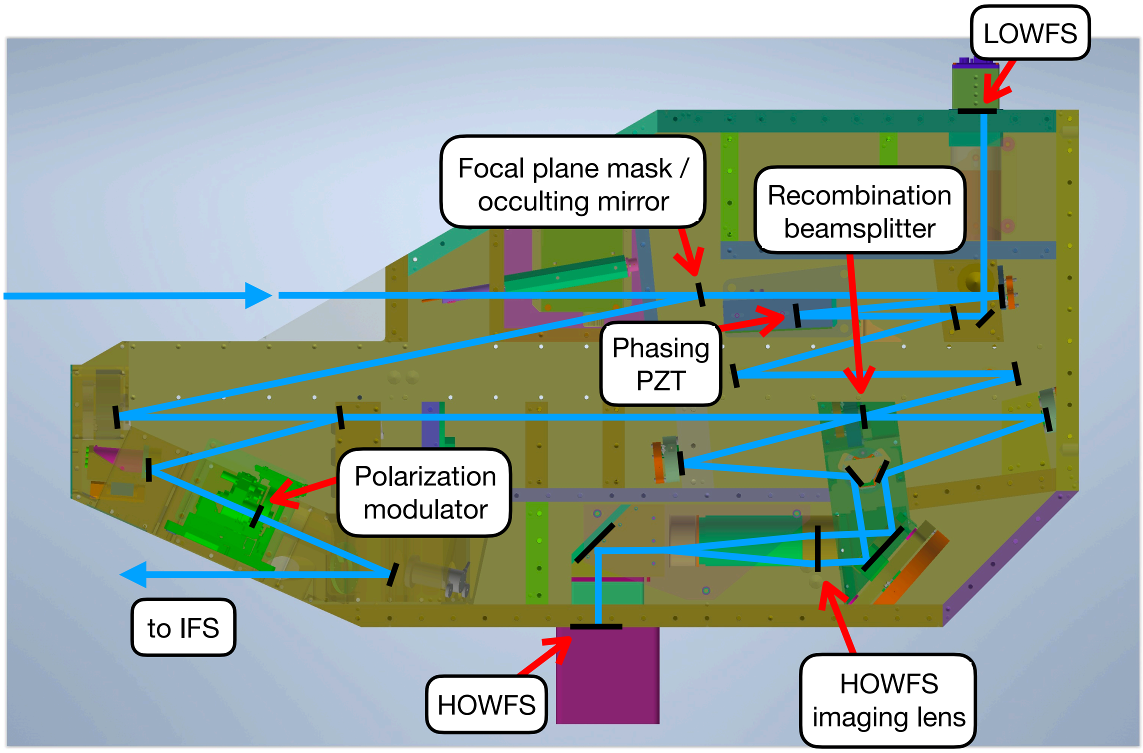

Figure 3: The GPI 1.0 CAL. (E.g., [5].)

- 942: Night-time Calibration Measurements. Execution times took about 80 seconds for 3 of 4 wavelength bands (with goal of 60 sec). The impact is minimal, because these measurements are only to be taken at the start of a science observing sequence ($\lesssim$5 per night).
- 970: CAL tilt update rates and precision. Update rates of 0.11 Hz were possible, though the goal was 0.25 Hz.
- 979: IFS optical feed (pointing only). Pointing and correction mirrors had a pointing repeatability with a standard deviation of $\approx$0.4 mas. This was short of the goal of 0.1 mas, but this requirement was loosened to 0.5 mas, as it was not thought to affect science data.
- 995: Focal plane mask (FPM) to IFS Lenslets Flexure and Thermal Registration. This is a failure only under the original requirement, but passes after propagating greater leeway allowed by the installation of an astrometry grid in a pupil plane upstream.
- 1210: Mechanism set time. Atmospheric dispersion corrector (ADC) separation took 45 sec, but this was the only mechanism out of 25 tested which took longer than the success criterion of 30 sec. Many mechanisms took much less than 30 sec.
- 1510: Science Instrument Detector. A sequential sequence of ten 2 sec frames took 188 sec, instead of the success criterion of 25 sec.

4. TESTS IN 2021, PRE-SHIPMENT IN CHILE

Following the international onset of the COVID-19 pandemic and the shutdown of all science operations at Gemini South in March 2020, the GPI instrument remained attached to the telescope's bottom Cassegrain port. When science operations resumed with reduced on-site personnel in October, instruments which were continuing to do science were a first priority. GPI was eventually removed from the telescope in January 2021.

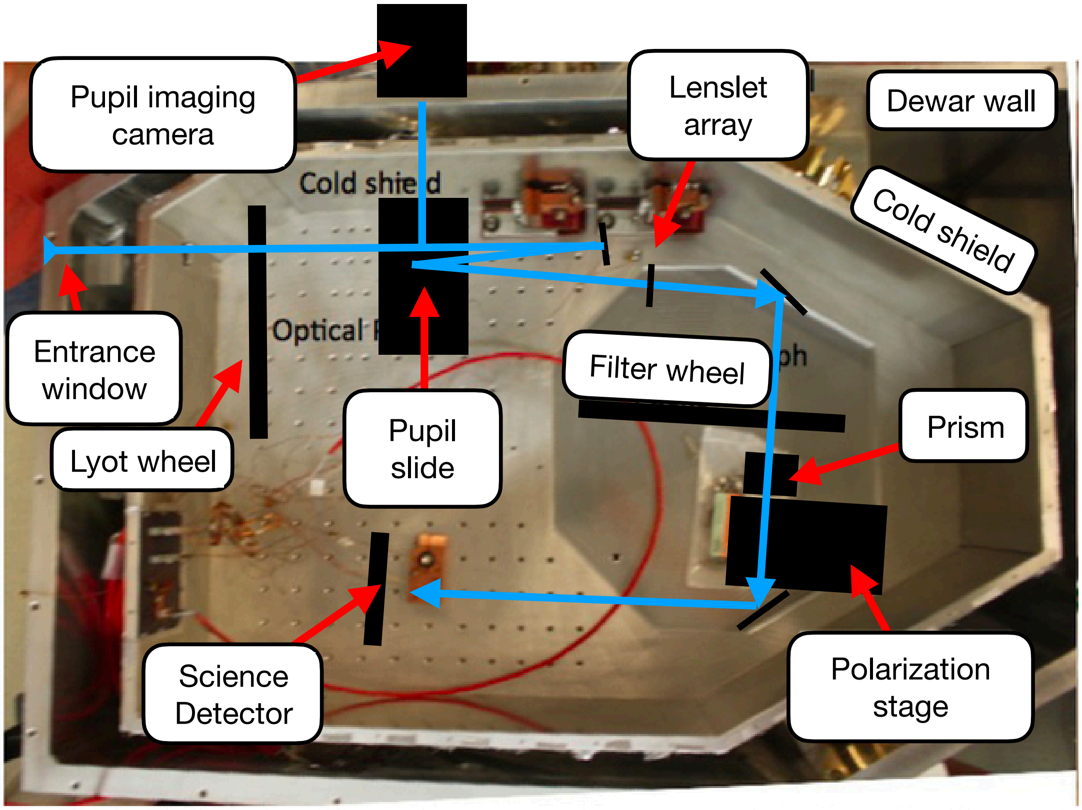

Figure 4: The GPI 1.0 IFS. The light ray schematic is overlaid on a picture of the unpopulated bench in Fig. 6 in [6].

After GPI was installed on a cart and attached to environmental and control umbilicals, in spring 2021 members of the GPI collaboration sitting in San Diego and Notre Dame remotely carried out all the FPR tests that could be conducted insofar as GPI was now immobilized and only had one broadband artificial light source available. GPI ultimately departed Gemini South for the U.S. in early May 2022, and arrived at the University of Notre Dame in June.

Of tests that could be performed, but whose results were different from 2013 results were the following (Table 1). These involved failures that turned into passes, and may be attributable to post-integration instrument improvements including software upgrades:

- FPR 970: Tilt update rates and precision: these now passed, whereas they failed in 2013..
- 979: IFS optical feed: CAL-IFS pointing and correction (P&C) mechanisms had precision of ≈0.4 mas in 2013 (a failure), which improved to <0.05 mas (a pass).

Significant aspects that could not be tested included polarization and throughput (no calibrated light source); flexure (no flexure stand); thermal effects (no cold chamber); and one translation axis of the AO wavefront sensor (AOWFS) spatial filter was not functioning, so this filter was not manually moved. In addition, speckle nulling has never been fully commissioned.

Table 1: GPI system test results

FPR Requirement	**Result (2013, UCSC)**	**Result (2021, Chile)**
FPR 140: Observing efficiency → Instrument acquiring science target photons >90%, exclusive of weather, down-time attributed to other systems, or telescope acquisition.	FAIL	FAIL
150: Non-common Path Flexure → Less than ∼10s μm at AO and coronagraph elements, and ≤1 IFS lenslet	PASS	N/A
175: Wavelength Bands → Shall cover in a single exposure any one of J, H, K1 or K2 bands.	PASS (most filters)	Inconclusive
180: Internal Static Contrast Ratio → Contrast ratio of 10^{-7} at $6\lambda/D$ at $\lambda = 1.6$ μm, using an artificial source	FAIL	FAIL*
210: Optical Throughput → Total throughput of the system of 13% in H band	PASS	N/A
340: Instrumental Polarization and Stability → Optical path upstream of the polarization modulator, excluding telescope optics, will have a total and stable linear polarization of less than 10%	PASS	N/A
390: Plate Scale Stability → Change of ≤0.2% over 4 hrs, 30 degree orientation change and 3.2°C temperature change.	PASS	PASS*
470: Inner Working Distance (IWD) → Coronagraph module shall achieve the throughput specifications at IWD=4λ/D.	PASS	PASS
620: Spectral Resolution → Average $R = [\lambda/\Delta\lambda$ per 2 pixels$] \geq 40$ in H band and ≥ 30 in other bands	PASS	PASS
670: Image Scale → 14 ± 0.5 mas/pixel	PASS	PASS
680: Pupil Viewing Mode → Resolution: H-band pupil imaging mode with >200 pixels across the Gemini pupil. Sensitivity: Shall achieve a SNR of 10:1 per pixel in 1 second on a 5th H magnitude star with the coronagraph.	PASS resolution FAIL sensitivity	N/A resolution FAIL sensitivity
690: Polarimetry → A dual-channel polarization analyzer will permit simultaneous observation of linear orthogonal polarizations (and all Stokes parameters with an external modulator mechanism).	PASS	N/A

—Table continued further below—

[a] using mean value
[b] under most stringent of two requirements
N/A: could not test
*: some subcomponents of test could not be performed

Table 1: GPI system test results —*continued*

FPR Requirement	**Result (2013, UCSC)**	**Result (2021, Chile)**
845: Object Saturation → Science detector will be capable of having an exposure time of ≤ 0.25s.	PASS	PASS
852: Integration Times → Science detector will support integration times of 1.5 to 900 seconds for a full frame image	PASS	PASS
940: Initial Calibration Measurements → GPI will take ≤2.5 hours a day for all required daytime calibrations	PASS	PASS
942: Night-time Calibration Measurements → Night-time calibrations at the beginning of a science observing sequence shall require ≤60 seconds	FAIL	FAIL
970: Tip/Tilt (TT) Updates Rates and Precision → CAL will update tilt information at 0.25 Hz, with a precision of 2 mas/update on an 8th magnitude star.	FAIL TT precision FAIL TTupdate rate	PASS TT precision PASS TT update rate[a]
972: Tilt Accuracy → The CAL will achieve an absolute accuracy in tilt at the FPM of 3 mas during a 1 hour exposure.	PASS	PASS
979: IFS Optical Feed → Motion resolution of the CAL-IFS P&C mechanisms will be ≤ 0.1 mas pointing, ≤0.05% pupil steering	FAIL pointing[b] PASS centering	PASS pointing N/A centering
981: Input Calibration Source → Broadband-light source output from 1.0 to 2.0 μm, I-band magnitude range 5th - 10th mag, 50 mas/30 μm repeatable positioning	PASS	PASS*
983: AOWFS Pointing and Centering (P&C) → P&C shall have pointing resolution of < 1 mas and centering resolution of < 0.1% of pupil diameter	PASS pointing PASS centering	PASS pointing N/A centering
987: Mechanisms → Input shutter will have configuration time ≤5s; spatial filter mechanism will provide a continuously variable square opening of 0.0 to ≥1.8 arcsec on a side; an AOWFS filter selector will have at least 6 positions; an ADC mechanism will accomodate any zenith orientation.	PASS	PASS*
989: AO Pupil Flexure & Thermal Requirements → Pupil registrations between tweeter and the coronagraphic pupil plane mask (PPM) don't move out of alignment by more than 0.4% of the pupil diameter	PASS	N/A
991: AOWFS to Tweeter Flexure and Thermal Registration → AOWFS lenslets will remain registered with the tweeter DM to within 10% of a lenslet pitch RMS	PASS	N/A

—*Table continued further below*—

[a] using mean value
[b] under most stringent of two requirements
N/A: could not test
*: some subcomponents of test could not be performed

Table 1: GPI system test results —*continued*

FPR Requirement	**Result (2013, UCSC)**	**Result (2021, Chile)**
993: Pupil plane mask (PPM) to Lyot Flexure and Thermal Registration → PPM pupil will remain registered with the Lyot pupil to within 1% of the pupil diameter under any normal operating gravitational vector and range of temperatures	PASS	N/A
995: FPM to IFS Lenslets Flexure and Thermal Registration → FPM (occultor) will remain registered with the IFS lenslets to within 4 μm under any normal operating conditions for a 10 degree change in elevation	PASS[a] FAIL[b]	N/A
1030: Thermal Gradients and Transients → Will meet performance requirements over one-hour observation sequence operation during which the temperature changes by no more than the standard Gemini environmental rate (0.8°C/hour for CP), with per-target calibrations at the beginning of the 1-hour period	PASS	N/A
1090: Mass on instrument support structure (ISS) → GPI, including support frame, thermal enclosures, electronics, cabling, services connections and coolant (i.e. all mass mounted on the ISS) will have a total mass of 2000 kg.	PASS	N/A
1100: Center of Gravity → GPI will exhibit, for the total ISS mass, a centre of gravity located 1000 mm out from the ISS mechanical interface (i.e. into GPI) on a line perpendicular to the centre of the science port. The tolerance is such that the out-of-balance will not exceed 400 Nm with respect to the telescope elevation axis.	PASS	N/A
1210: Mechanism Set Time → Mechanisms will have a maximum set time of 30s	PASS[c]	PASS*[d]
1220: Mechanism Configuration Time → A complete reconfiguration of GPI (i.e. all mechanisms) will be performed in less than 60s	PASS	PASS
1230: Repeatability of Configuration → Total error at the IFS lenslet plane resulting from a total reconfiguration will be less than 0.5 lenslets	PASS multiband PASS flexure	PASS multiband N/A flexure
1450: Temperature Rate of Change → Maximum rate of change of the detector is 0.25 K/min.	PASS	N/A
1470: Environmental Monitoring → Control system will monitor and permit turning on/off the logging of environmental conditions within GPI.	PASS	PASS
1510: Science Instrument Detector → Software system will not add to the overhead for readout in any way that increases the readout rate	FAIL	FAIL

[a] using mean value
[b] under most stringent of two requirements
N/A: could not test
*: some subcomponents of test could not be performed

5. COMPARISON

The 2013 and 2021 tests in Table 1 indicate little change to the instrument over the preceding eight years, insofar as it could be tested. Repeat failures mostly amount to slightly reduced data-taking efficiency. The largest changes in the test results between 2013 and 2021 are actually failures that turned into passes. However, the 2021 tests do not characterize flexure, throughput or polarization, or thermal effects. These tests also did not cover "track assembly" crashes, which involve software meant to guard against mechanical flexure. These types of crashes during the original GPI campaign caused some downtime, and tests are being carried out to attempt to diagnose the problem.

6. CONCLUSION

The instrument has aged well, and we see no particular causes for concern from these tests before the upgrade process. Now that GPI has arrived at the University of Notre Dame, we will re-perform tests once again to see how the instrument weathered the shipment process. After the instrument is upgraded at Notre Dame, testing will be performed yet again, at which point the instrument's scientific performance is expected to have improved on a number of metrics.

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REFERENCES

[1] Nielsen, E. L., De Rosa, R. J., Macintosh, B., Wang, J. J., Ruffio, J.-B., Chiang, E., Marley, M. S., Saumon, D., Savransky, D., Ammons, S. M., et al., "The gemini planet imager exoplanet survey: giant planet and brown dwarf demographics from 10 to 100 au," *The Astronomical Journal* **158**(1), 13 (2019).

[2] Chilcote, J. K., Bailey, V. P., De Rosa, R., Macintosh, B., Nielsen, E., Norton, A., Millar-Blanchaer, M. A., Graham, J., Marois, C., Pueyo, L., et al., "Upgrading the gemini planet imager: Gpi 2.0," in [*Ground-based and Airborne Instrumentation for Astronomy VII*], **10702**, 1070244, International Society for Optics and Photonics (2018).

[3] Chilcote, J., Konopacky, Q., De Rosa, R. J., Hamper, R., Macintosh, B., Marois, C., Perrin, M. D., Savransky, D., Soummer, R., Véran, J.-P., et al., "Gpi 2.0: upgrading the gemini planet imager," in [*Ground-based and Airborne Instrumentation for Astronomy VIII*], **11447**, 394–407, SPIE (2020).

[4] Poyneer, L. A., Palmer, D. W., Macintosh, B., Savransky, D., Sadakuni, N., Thomas, S., Véran, J.-P., Follette, K. B., Greenbaum, A. Z., Ammons, S. M., et al., "Performance of the gemini planet imager's adaptive optics system," *Applied Optics* **55**(2), 323–340 (2016).

[5] Wallace, J. K., Angione, J., Bartos, R., Best, P., Burruss, R., Fregoso, F., Levine, B. M., Nemati, B., Shao, M., and Shelton, C., "Post-coronagraph wavefront sensor for gemini planet imager," in [*Adaptive Optics Systems*], **7015**, 1879–1890, SPIE (2008).

[6] Larkin, J. E., Chilcote, J. K., Aliado, T., Bauman, B. J., Brims, G., Canfield, J. M., Cardwell, A., Dillon, D., Doyon, R., Dunn, J., et al., "The integral field spectrograph for the gemini planet imager," in [*Ground-based and Airborne Instrumentation for Astronomy V*], **9147**, 590–602, SPIE (2014).

[7] Thomas, S. J., Poyneer, L., De Rosa, R., Macintosh, B., Dillon, D., Wallace, J. K., Palmer, D., Gavel, D., Bauman, B., Saddlemyer, L., et al., "Integration and test of the gemini planet imager," in [*Astronomical Adaptive Optics Systems and Applications IV*], **8149**, 21–33, SPIE (2011).

[8] Macintosh, B. A., Anthony, A., Atwood, J., Barriga, N., Bauman, B., Caputa, K., Chilcote, J., Dillon, D., Doyon, R., Dunn, J., et al., "The gemini planet imager: integration and status," in [*Ground-based and Airborne Instrumentation for Astronomy IV*], **8446**, 648–656, SPIE (2012).