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Status of the PALM-3000 high-order adaptive optics system

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ABSTRACT

The PALM-3000 upgrade to the Palomar Adaptive Optics system will deliver extreme adaptive optics correction to a suite of three infrared and visible instruments on the 5.1 meter Hale telescope. PALM-3000 uses a 3388-actuator tweeter and a 241-actuator woofer deformable mirror, a wavefront sensor with selectable pupil sampling, and an innovative wavefront control computer based on a cluster of 17 graphics processing units to correct wavefront aberrations at scales as fine as 8.1 cm at the telescope pupil using natural guide stars. Many components of the system, including the science instruments and a post-coronagraphic calibration wavefront sensor, have already been commissioned on the sky. Results from a laboratory testbed used to characterize the remaining new components and verify all interfaces are reported. Deployment to Palomar Observatory is planned August 2010, with first light expected in early 2011.

Keywords: Extreme Adaptive Optics, Extrasolar Planets

1. INTRODUCTION

Since the discovery of the first substellar object at Palomar Observatory in 1995[1], improvements in adaptive optics (AO) performance have gradually driven the detection limit of such objects down into the planetary regime. In the last five years, several extrasolar planet candidates have been directly imaged using VLT, Keck, and Gemini AO systems[2,3,4]. All of these detections were around particularly young stars (<100 Ma), and with contrast ratios less than 10^4:1. Unlike planets studied by indirect techniques, those directly imaged using adaptive optics offer the exciting possibility of the detailed study of their surfaces and atmospheres, and potentially their biospheres.

With a predicted RMS residual wavefront error of 90 nm in median atmospheric conditions – equivalent to a Strehl ratio of 89% in H band (1.64 μm wavelength) – the PALM-3000 AO system is specifically designed to detect and characterize extrasolar planets. Using the Project 1640[5] coronagraphic integral field spectrograph (IFS) built by the American Museum of Natural History (see Figure 1) and a post-coronagraphic calibration wavefront sensor contributed by the NASA Jet Propulsions Laboratory, we expect to reach contrast levels of greater than 10^6:1 at 0.5 arcseconds from bright stars in the raw data. Post-processing techniques which distinguish quasi-static atmospheric and instrumental speckles from astrophysical sources based on their spectral signature should extend companion detectability nearly another order of magnitude[6]. This will bring the super-Jupiters of older stellar systems, and lower mass planets (approaching 1 M_J) in young systems, within reach of observation. Most importantly, the IFS will gather low-resolution spectra of each candidate, addressing such questions as the temperature and atmospheric composition of these alien worlds.

Compared to planned high-contrast AO systems on larger telescopes[7,8,9], PALM-3000 benefits from a higher spatial bandwidth of correction and a larger control radius. Although high-contrast detection capability theoretically scales as D^4/σ^2, where D is the telescope diameter and σ is the residual RMS wavefront error, systematic errors actually limit all existing high-contrast instruments. By controlling high spatial frequency systematic errors, the current Palomar AO

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system already obtains contrast comparable to the best ground-based measurements on larger telescopes[10]. The high actuator density and smaller aperture additionally leads to a larger control radius $N\lambda/2D$, where N is the number of actuators across the pupil. We therefore expect the "dark hole" of PALM-3000 to extend to 2.1 arcseconds radius at λ=1.64 µm, leading to a potential discovery volume many times larger than that of other planet-finding instruments.

Two additional instruments, each addressing different scientific goals and already in use with the PALMAO system, complete the PALM-3000 suite. The PHARO infrared camera and spectrograph[11] provides imaging and grism spectroscopy at 0.96-2.5 µm wavelength over a 25-40 arcsecond field. With great flexibility and only 35 nm of internal wavefront error, PHARO is routinely used to test novel coronagraphic techniques[12,13] and is well suited for use with PALM-3000. The SWIFT I-z band AO-assisted integral field spectrograph[14] is designed to complement diffraction-limited near-infrared IFS on 8-10m class telescopes in resolution and sensitivity by combining high order AO correction, low sky background, and sensitive deep depletion CCDs. It will benefit from the greatly improved correction in the visible provided by PALM-3000.

The PALM-3000 project is an upgrade to the successful PALMAO system[15] currently in service at the Cassegrain focus of the 5.1 meter Hale Telescope at Palomar Observatory. It will reuse many of the components of the current system, including the optical bench and telescope mounting interface, handling fixtures, calibration sources, 241-actuator deformable mirror, and most large optics. Added to these will be a state-of-the-art 3388-actuator tweeter deformable mirror, a wavefront sensor with up to 63×63 sampling in the pupil plane, and a new wavefront reconstructor computer. The design of these components has been described previously[16,17,18]. This paper presents an update on the status of integration and commissioning.

Figure 1. The PALMAO system and Project 1640 coronagraphic integral field spectrograph mounted at the Cassegrain focus of the Palomar Hale telescope.

2. OPTICAL RELAY

The design of the PALM-3000 optical relay was constrained by the need to reuse the optical bench and off-axis parabolas, and preserve the location of the science focus for compatibility with the current PALMAO instruments. The layout of the optical relay is illustrated in Figure 2. The optical bench will be mounted parallel to the Cassegrain mounting flange, with alignment and calibration sources located in the intervening space. The telescope beam passes through a hole in the bench to the relay optics mounted on the far side.

Two flats in a "figure 4" (FM1 & FM2) fold the beam into the relay. The relay consists of an off-axis parabola (OAP1), a fold flat (FM3), tip/tilt mirror (TTM), woofer DM (LODM), tweeter DM (HODM), fold flat (FM4), and the second off-axis parabola (OAP2). A manually selectable dichroic in a gimbal mount (SSM1) reflects shorter wavelengths towards a second gimbaled mirror (SSM2) and the wavefront sensor and acquisition camera (HOWFS, ACam). Dichroics with cutoff wavelengths of λ=650, 750, 960, and 1050 nm, and a 50/50 beamsplitter, are available for use with the various science instruments.

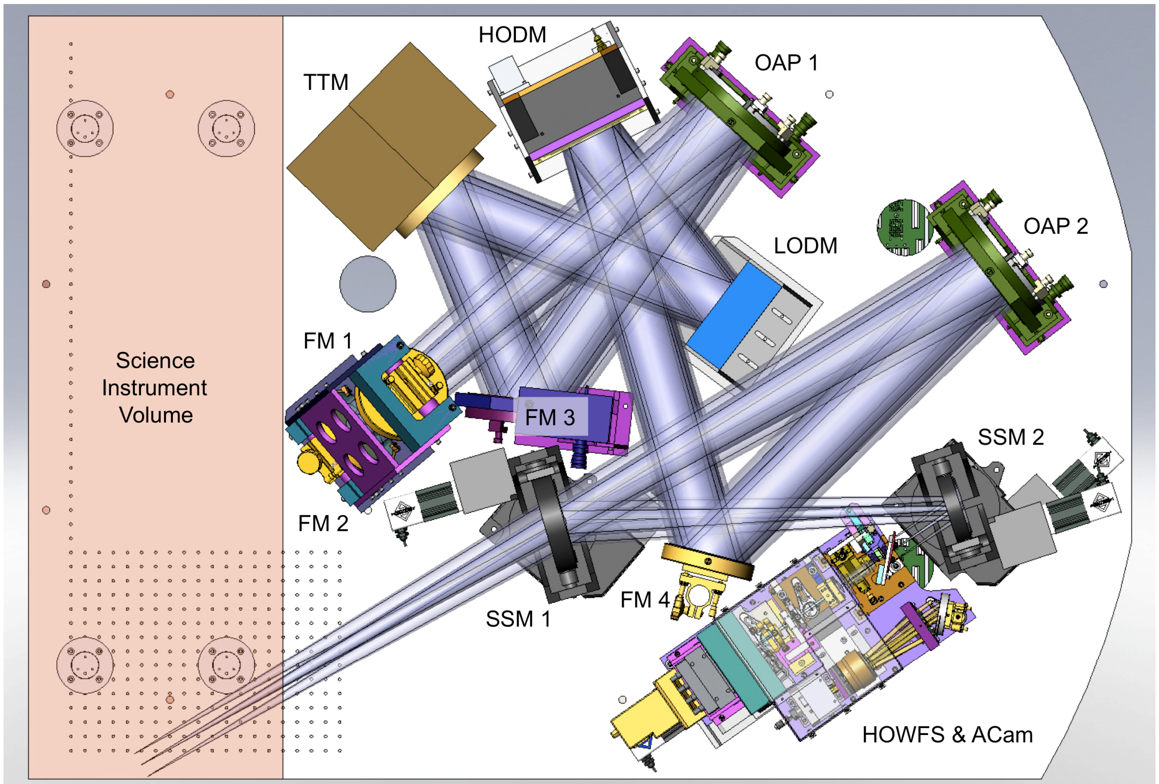

Figure 2. Rendering of the PALM-3000 optical bench with enclosure and cables hidden, showing a 120 arcsecond diameter beam. The components illustrated hang below the optical bench when installed at the Cassegrain focus of the Hale telescope.

The optical relay passes an unvignetted 120 arcsecond diameter field to the science focus. This wide field was preserved to allow the future addition of laser guidestar capability. With on-axis static aberrations corrected by the deformable mirrors (primarily astigmatism due to the tilted dichroic, and tolerance for alignment error), field aberrations at the extreme corners of the largest science field, 30 arcseconds off axis, will suffer just 32 nm of RMS wavefront error.

3. DEFORMABLE MIRRORS AND WAVEFRONT SENSOR

High spatial frequency wavefront control is provided by a Xinetics Inc. photonex module deformable mirror with 3388 active actuators on a 66×66 grid with 1.8 mm pitch and 1.1 µm stroke (HODM, Figure 3, left). The mirror has been thoroughly tested in the laboratory, and characterization results are reported in Roberts et al.[19] Approximately 10 nm RMS of high spatial frequency error remains when the mirror is controlled to a flat surface, meeting the PALM-3000 contrast requirements (Figure 1, right)

A second "woofer" DM (LODM) provides the additional stoke required to compensate atmospheric turbulence across the 5.1 m aperture. We are reusing the PALMAO DM for this purpose, which has 241 active actuators on a 7.0 mm pitch and 4 µm of stroke. The tweeter DM is located at the pupil with an angle of incidence of 10.5°, while the woofer is at a conjugate height of +792 m and 16.0° incidence. The woofer conjugate height has been minimized to reduce focal plane distortions caused by compensating low-order modes at a non-pupil conjugate.

Electronics and cabling for the high-order DM have proven to be one of the more costly implementation issues. The two full-height racks of high-voltage drivers dissipate 6 kW, and must be located on the telescope near the deformable mirror. This has required retrofitting the 62-year-old Hale telescope with additional power circuits and a liquid cooling system. The cables running from drivers to the mirror have also required a significant redesign to facilitate making the 4752 necessary electrical connections (4356 actuator signals and 396 bias voltages) in a reasonable amount of time during daytime installation of the PALM-3000 system. This has been implemented using 16 240-conductor cables with Hypertronics N series connectors at each end.

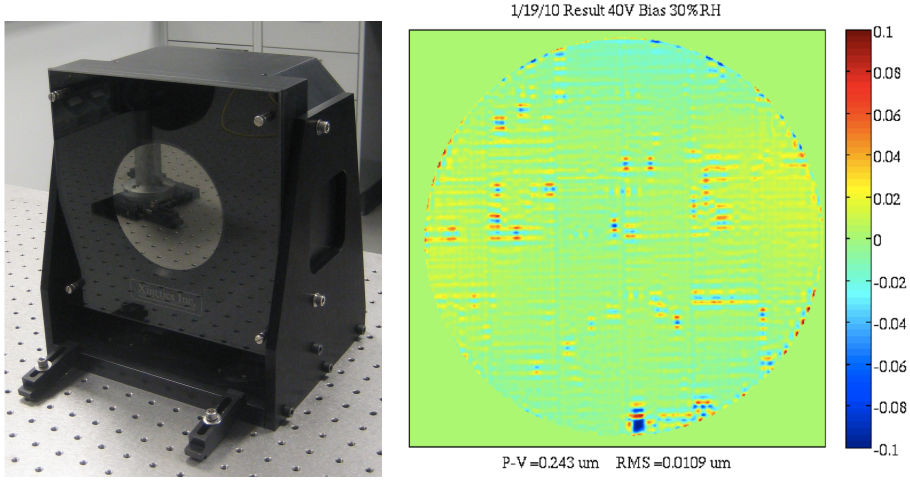

Figure 3. *Left:* The 3388 active actuator Xinetics deformable mirror in the laboratory at Caltech. *Right:* Deformable mirror surface figure with actuators commanded to flatten the mirror (scale in microns). An RMS surface error of 11 nm remains on a scales finer than the actuator spacing.

PALM-3000's deformable mirrors will be driven by signals from a high order Shack-Hartmann wavefront sensor (HOWFS) which supports adjustable pupil sampling and frame rates. Selection of the pupil sampling is achieved with a microlens array exchange mechanism which can select from four different microlens arrays that span 8, 16, 32 and 63 subapertures across the re-imaged pupil. Control over the spatial and temporal pupil sampling serves to minimize total wavefront reconstruction error over a wide range of guide star brightness[20], which maximizes the delivered Strehl ratio. The sensor incorporates a tilted spherical mirror and cylindrical lens to produce an elliptical pupil at the microlens arrays, matching the lens pitch to the high-order DM actuators which appear foreshortened due to the 10.5° angle of incidence reflection at the high-order deformable mirror. An adjustable field stop has been included to minimize aliasing error. For a full description of the wavefront sensor design, see Baranec (2008)[17].

4. WAVEFRONT CONTROL

The PALM-3000 wavefront processor computer has been specified to perform full vector matrix multiplication reconstruction of the guidestar wavefront at 63×63 sampling and 2 kHz frame rate[18]. With a total of 3631 actuators to control and 8192 slope measurements (though some fall outside the illuminated pupil, they are included in the calculation for symmetry), the computational problem is over 2 orders of magnitude larger than that for the most complex current astronomical AO systems. Our solution uses 17 NVIDIA model 8800 graphics processor units (GPUs) hosted in a cluster of 9 desktop personal computers running a standard Linux operating system, all located in a computer room remote to the instrument. Using entirely off-the-shelf hardware, a GPU cluster provides the greatest ease of use, potential upgradeability, and cost savings. By dividing the primary wavefront reconstruction computation between 16 GPUs and further processing the HOWFS subapertures in two sequential batches (beginning when just half the pixels have been read out) a total computational latency of only 222 μs is achieved. Offload commands between adaptive mirrors will be computed on the 17th GPU. We expect that the latency can be further reduced by future upgrades of the GPUs, which enjoy a rapid development cycle due to strong commercial demand.

We have implemented a flexible servo control architecture to facilitate the testing of several control schemes. A block diagram is illustrated in Figure 4. For initial commissioning with 63×63 subapertures across the pupil, we will directly control the HODM using a regularized zonal reconstructor[21] which relies on the Fried geometry of the HODM actuators and subapertures (mode 1). An independent loop operating with a 1-frame delay then computes the projection of the HODM surface shape onto the LODM actuators, and offloads these low-order modes. An alternative control scheme (mode 2) is planned for the other pupil sampling modes, in which a reconstructor matrix computed following the prescription of Conan et al.[22] splits commands to the two deformable mirrors based on spatial frequency. Approximately 3000 modes orthogonal to the LODM actuator influence functions with controlled with the HODM.

Both servo modes will benefit from two-stage tip/tilt control (first with the HODM or LODM, then offloaded to the TTM), allowing us to benefit from the higher control bandwidth of the DMs with respect to our rather sluggish monolithic TTM. The shape each mirror assumes in the absence of an error signal is determined by a “flatmap”, added with low gain to the leaky integrator for each mirror.

During operation with the Project 1640 instrument, the post-coronagraphic calibration wavefront sensor will provide high spatial frequency “truth” at the coronagraphic stop, approximately once per minute. This sensor was commissioned with the PALMAO system in spring 2010, and is already capable of reducing the quasi-static errors with this lower order AO system to ~18 nm RMS. Additional calibration and alignment improvements should reduce this to <3 nm RMS with PALM-3000. The calibration wavefront sensor error signal will be incorporated into the offsets to which the HOWFS centroids are driven (correcting spatial frequencies limited by the HOWFS pupil sampling), and added to the HODM flatmap (potentially correcting higher spatial frequencies, limited only by the DM actuator count).

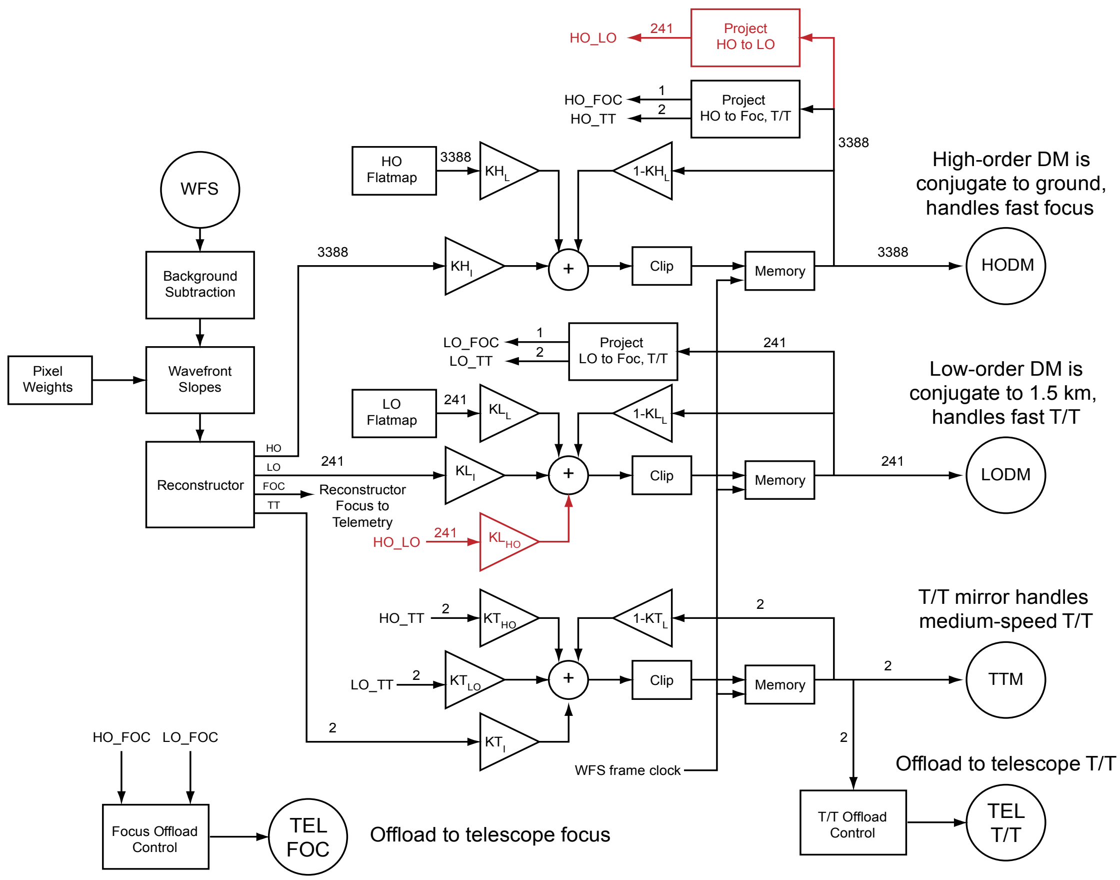

Figure 4. Block diagram of the PALM-3000 servo control mode 2. In this mode, the residual wavefront measured by the HOWFS is split by spatial mode between the HODM and LODM. The Project 1640 calibration wavefront sensor will update the HOWFS centroid offsets and the “HO flatmap” to which the HODM is driven in the absence of an error signal.

5. INTEGRATION AND TESTING

A laboratory testbed for PALM-3000’s new components and interfaces has been operating at Caltech since November 2009 (see Figure 5, top). Using a refractive relay in place of the off-axis parabolas of the final system, a monochromatic light source is collimated, reflected off the HODM at 10.5° incidence angle, and refocused to the HOWFS field stop. A Zygo phase-shifting interferometer simultaneously measures the HODM surface figure at 0° incidence angle. As subsystems have been completed, they have been integrated into the testbed, allowing us to verify optical, electronic, and software interfaces, and characterize the performance of each subsystem. The full complement of electronics and cabling are used to control the HOWFS and HODM, while the wavefront processor computer cluster is housed in the laboratory next door. The ability to test all the new components and interfaces prior to decommissioning the PALMAO system significantly reduces risk during the final integration phase, and the total down-time for AO operations at Palomar observatory.

To date we have fully integrated the HOWFS, HODM, publish-subscribe software environment and graphical user interface, and tested wavefront reconstruction in servo mode 1 (Figure 5, bottom). Our current efforts are focused on verifying the high-speed control of the HODM and the closed-loop performance of the testbed system. We expect to complete these tasks in July 2010, paving the way for a pre-ship review and shipment to Palomar of the PALM-3000 components in August 2010. Final integration with the currently-fielded components, including the 241-actuator LODM and the Project 1640 calibration wavefront sensor, will take place in the fall and early winter of 2010.

First light of the PALM-3000 system is planned for February 2011, with commissioning with all three instruments (PHARO, Project 1640, and SWIFT) extending through July. We expect to begin the 99-night Project 1640 key science survey of 250 nearby bright stars for low-mass and planetary companions in August 2011.

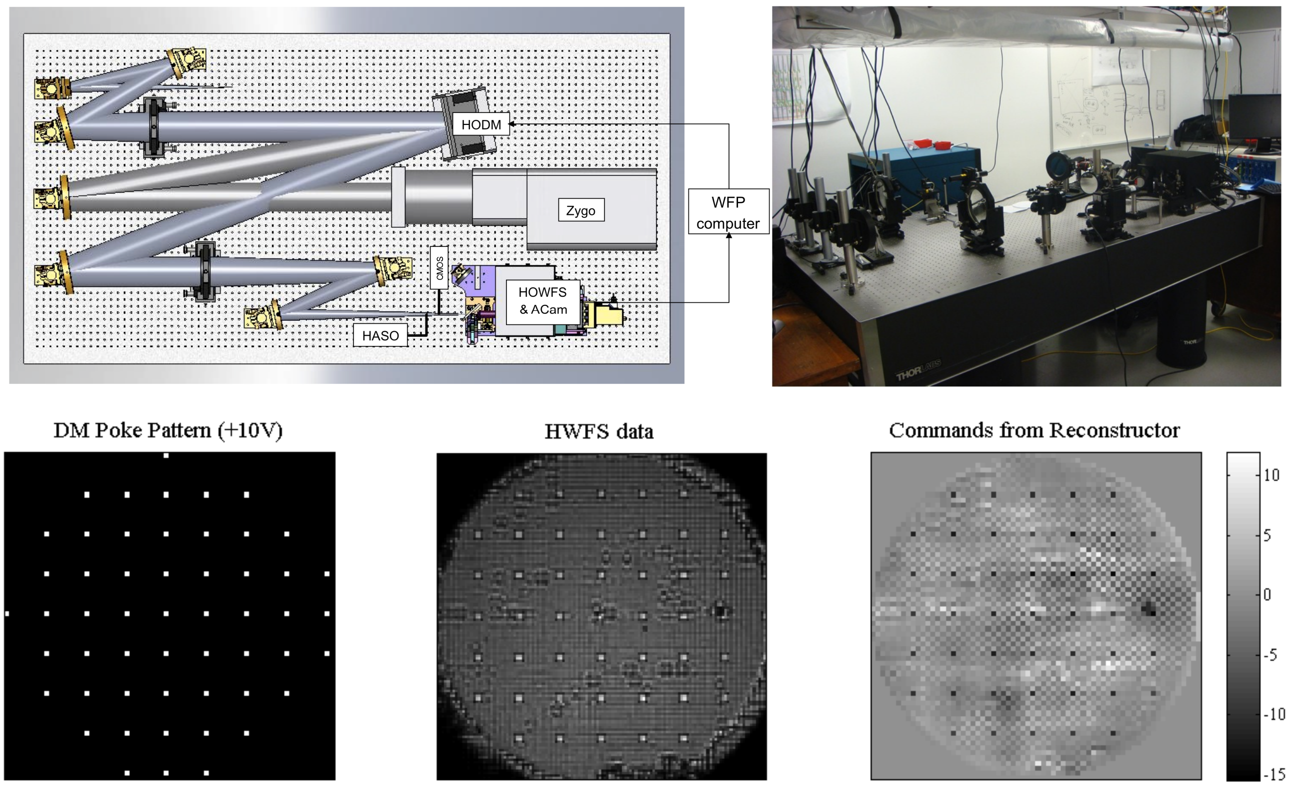

Figure 5. *Top left:* Layout of the PALM-3000 testbed at Caltech. *Top right:* Photo of the testbed in February 2010. *Bottom left:* Map of voltages applied to the HODM during an experiment to test wavefront reconstruction. *Bottom center:* Resulting pixel values in HOWFS. *Bottom right:* Result of wavefront reconstruction calculation performed at 500 Hz.

6. CONCLUSIONS

With 3388 active actuators, PALM-3000 will be the highest order adaptive optics system ever deployed for astronomy. It will deliver high Strehl in the near-infrared (89% in H band) and diffraction-limited correction throughout the visible to a suite of instruments optimized for low wavefront error science. Using bright natural guide stars, the Project 1640 coronagraphic IFU should achieve contrast levels of better than 10^6:1 at 0.5”, allowing the direct imaging and spectroscopic study of Jovian planets around nearby young stars. The successful integration of all of PALM-3000’s new components on a laboratory testbed has given us confidence that the final system will meet its scientific goals. We expect the testbed phase to conclude in August 2010, to be followed by final integration with the PALMAO components in fall 2010, and PALM-3000 first light in February 2011.

ACKNOWLEDGMENTS

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