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Richard Dekany, Antonin Bouchez, Matthew Britton, Viswa Velur, Mitchell Troy, J. Chris Shelton, Jennifer Roberts, "PALM-3000: visible light AO on the 5.1-meter Telescope," Proc. SPIE 6272, Advances in Adaptive Optics II, 62720G (28 June 2006); doi: 10.1117/12.674496

SPIE. Event: SPIE Astronomical Telescopes + Instrumentation, 2006, Orlando, Florida , United States

PALM-3000: Visible-light AO on the 5.1-meter Telescope

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ABSTRACT

PALM-3000 is proposed to be the first visible-light sodium laser guide star astronomical adaptive optics system. Deployed as a multi-user shared facility on the 5.1 meter Hale Telescope at Palomar Mountain, this state-of-the-art upgrade to the successful Palomar Adaptive Optics System will have the unique capability to open the visible light spectrum to diffraction-limited scientific access from the ground, providing angular imaging resolution as fine as 16 milliarcsec with modest sky coverage fraction.

Keywords: Adaptive optics, laser guide star, sodium laser, visible adaptive optics, instrumentation, ground-based telescopes

1. INTRODUCTION

Adaptive optics (AO) systems developed over the last six year have opened up important new areas of astronomical research, overcoming atmospheric degradations to achieve diffraction-limited imaging and spectroscopy on 5-10 meter diameter telescopes. Until now, technology has constrained AO capability on large apertures to infrared wavelengths, with visible wavelength capability restricted to astronomical telescopes[1] of 2.5 m diameter, and military systems of 3.6 m diameter[2]. Traditionally, the primary constraints have been the lack of high-actuator-count deformable mirrors (DMs), powerful guide star lasers (Figure 1), and the processing limitations of prevailing computer technology. Recent advances in each of these component technologies, however, have opened the door to diffraction-limited visible-light science on telescopes as large as 5.1 meters. Systems once considered too challenging are now practical, opening an entirely new capability to our national science infrastructure.

We describe here key aspects of the first *visible* light sodium laser-guide-star astronomical adaptive optics system, to be deployed as a multi-user shared facility on the 5.1 meter Hale Telescope at Palomar Mountain. PALM-3000 represents a state-of-the-art instrument upgrade, building on the existing successful near-infrared Palomar AO system, that will have the unique capability to:

- Open the *visible* light spectrum to diffraction-limited scientific access from the ground, enabling spatial resolution as fine as 16 milliarcseconds (78 nanoradians), providing resolution synergy with near-IR AO systems on 8-10m telescopes, such as Gemini Observatory.
- Provide ~300 times the *visible* point source imaging sensitivity compared to current seeing-limited observations at Palomar.
- Extend the *infrared* and *visible* sky coverage fraction of sodium laser guide star (LGS) AO by better sharpening field stars that are necessary for tip/tilt wavefront measurement.

Furthermore, because of geometric limitations[ii] imposed by the Earth's mesospheric sodium layer, existing sodium laser guide star architectures on 8-10m telescopes will not routinely enable *visible* wavelength science. PALM-3000 will thus serve a pilot role unmatched on 8-10m telescopes for a decade.

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[ii] The finite-altitude sodium laser beacon samples a frustum of atmosphere, whereas natural starlight samples a cylinder.

Advances in Adaptive Optics II, edited by Brent L. Ellerbroek, Domenico Bonaccini Calia,
Proc. of SPIE Vol. 6272, 62720G, (2006) · 0277-786X/06/$15 · doi: 10.1117/12.674496

2. SCIENCE GOALS

Our astronomical research interests span a range of high-resolution applications uniquely enabled by the PALM-3000 upgrade. We list potential science programs with their corresponding AO system configuration and performance estimates in Table 1. In addition, three key science programs that we specifically intend to initiate with strong student involvement are described in detail.

2.1 Stellar Evolution via Pre-Main Sequence Binaries

The PALM-3000 upgrade will provide unprecedented spatial resolution imaging at visible wavelengths, improving investigations of pre-main sequence binary star systems (see Mathieu[3] et al 2000 for a review). Thus far, empirical masses have been derived for several eclipsing, double-lined, spectroscopic binaries (TY CrA[4]; RX J0529.4+0041[5]; and SM790[6]), but these are rare. In order to sample the full range of pre-main sequence star radii, we must measure orbital motion of visual pairs spanning a range of masses. To date, all binaries with good orbital solutions have component masses >0.7 M_{sun}; no dynamical mass constraints exist for young stars with masses <0.5 M_{sun}. Because the (logarithmic) peak of the stellar mass function occurs around 0.2 M_{sun} a large parameter space of fundamental astrophysics remains unexplored. Orbital separations probed by ground-based speckle, adaptive optics, and Hubble Space Telescope work in the infrared[7,8,9,10,11,12,13,14] extend inward only to tens of AU, limiting the constraint of models.

The PALM-3000 upgrade will improve background-limited point source sensitivity by over 6 magnitudes, surpassing the visible (red) light sensitivity of all current ground-based telescopes, regardless of diameter, as well as the HST. Furthermore, it will provide 0.028 arcsec resolution at 0.7 microns, a linear factor of ~30 improvement over median ambient seeing. At the distance of the nearest star-forming regions (e.g. Taurus at 150pc), this corresponds to < 5 AU. Of particular interest is the frequency distribution of orbital separations, which informs our understanding of the star formation process. This is especially true if environmental influences can be understood[15], for example, by moving from investigations at 150 pc out to the Orion regions at 480 pc, where separations as fine as 15 AU would still be observable. With visible imaging, we will obtain photometry in addition to orbital measurements. Photometry in the 0.6-0.9 μm region is crucial for pre-main sequence stars as this is the only wavelength range which probes the stellar photosphere.

2.2 Satellites of Kuiper Belt Objects (KBOs)

The PALM-3000 upgrade would be the first adaptive optics system in the world with the capability to lock on and track faint moving objects in the outer solar system. Because the system will have a uniquely low wavefront error, it will sharpen unresolved objects at visible wavelengths to the diffraction limit, allowing faint m_V ~21 Kuiper belt objects (KBOs) to be used for the first time as natural tip/tilt reference stars. This will enable the determination of satellite orbits for a significant number of small binary KBOs. HST surveys of faint KBOs have shown that at least 11% have satellites. Little is known about the orbits of the HST-discovered KBO satellites, however, due to the high cost (in number of HST orbits) of the long-term observations necessary for determining the orbital elements. The largest known KBOs, meanwhile, have a significantly higher binary fraction[16], and a recent study of their orbits[17] has revealed a surprising range of densities, from 0.7 to more than 2.6 g cm^{-3}. With PALM-3000, we will conduct the first large-scale survey of KBO masses by measuring their satellite's orbital elements. Such a survey, including resolved infrared spectroscopy of the primaries and satellites, can also illuminate the mechanism of the satellites' formation (whether by capture or impact) and the collisional history of the Kuiper Belt.

2.3 Direct Detection of Hot, Young Exo-Jupiters

Since the discovery[18] of the first substellar object at Palomar Observatory in 1995, improvements in AO performance have gradually driven the detection limit of such objects down into the planetary regime. In the last two years, three young extrasolar planet candidates were identified using the NACO adaptive optics instrument at the VLT[19,20,21]. All of these detections were at separations greater than 0.7 arcsec, and with contrast ratios less than 1,000:1. The success of these observations demonstrates that when searching for young exo-Jupiters it is important to not only achieve high contrast but to be able to search around relatively faint host stars.

Table 1. Science capability summary for PALM-3000. Each line of this table represents a potential science program enabled by the upgrade, the corresponding AO instrument configuration, and expected performance. (NGS indicates natural guide star mode; LGS indicates laser guide star mode.) N is the number of actively controlled actuators across the telescope pupil diameter. In all cases N=65 actuators will be used for static correction of telescope and instrument aberrations (including a guard ring). The faint tip/tilt guide star limits arise because these guide stars enjoy partial AO compensation. For LGS observations, we assume 16% R-band Strehl of the tip/tilt star is provided by the AO system well within the corresponding isoplanatic angle (~13 arcsec for 700 nm). We assume here a measured atmospheric seeing turbulence profile, scaled to $r_0(0.5\mu m) = 15$ cm.

Project	High-order guide star & limiting mag.	Tip-tilt guide star & limiting V-mag.	N	Strehl @ λ		Example Program
				%	μm	
Io surface geology	NGS / 5	the target object itself	63	36 53 89	0.55 0.70 1.65	5 km resolution at Io's surface
Surface mineralogy of Ceres / Pallas / Vesta	NGS / < 8	object itself	63	19	0.70	3 km resolution on brightest asteroids
Mira variables and supergiants	NGS / < 10	object itself	31	33 84	H-α 1.65	Several nearby targets
T Tauri objects and accretion disks	NGS / < 12	object itself	31	84	1.65	Approximately a dozen select targets
Precision faint star photometry in Orion	NGS / < 8	object itself	63	94	2.2	3% precision for dozens of stars to faintness $m_K = 22$
Hot, young exo-Jupiter study	NGS / < 6	object itself	63	94	2.2	100's of stars in nearest star-forming regions
	LGS / 7.4	target object / > 12 and < 21	31	85	2.2	Systems with primaries too faint for high-contrast NGS AO
Mass/luminosity studies of pre-main sequence binaries	LGS / 7.4	target object / < 17.5	31	22	0.80	100 binaries within 150 pc down to mV=15
Z = 0.5 galaxy morphology	LGS / 7.4	background star / < 18.9 w/in 8 arcsec	31	42 75	1.25 2.2	21 % sky coverage (galactic average)
Spectroscopy of Kuiper belt objects	LGS / 7.4	target object / < 21	31	17 52	1.25 2.2	Binarity determination of 100 KBOs

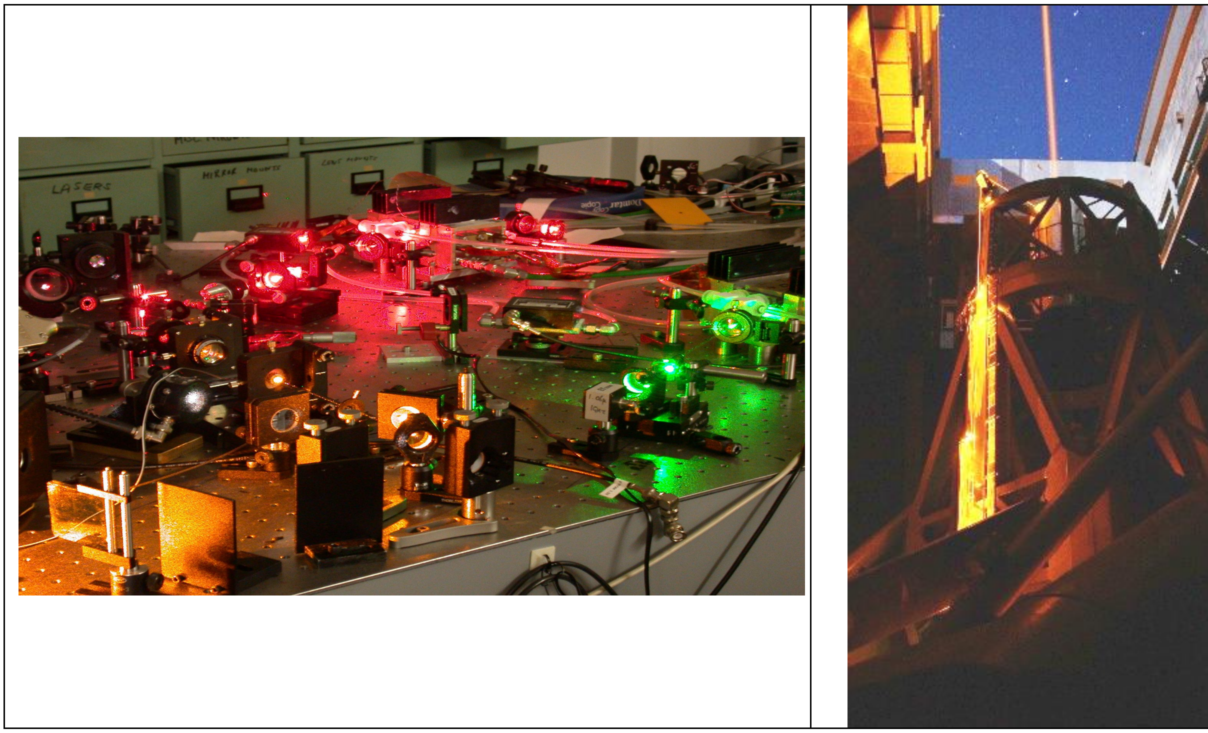

Figure 1. (Left) The successful 8.5W Chicago Sum-Frequency Laser (CSFL), showing yellow sodium 589nm light generation. (Right) Initial projection of the CSFL at Palomar Observatory (Oct. 2004). The laser resides in the Coude lab and is projected along a servo mirror system to a 50 cm diameter beam expander located behind the telescope secondary mirror, making optimal use of available laser power. We are currently pursuing upgrades to the CSFL, funded by NSF Center for Adaptive Optics, to achieve 20W of laser light by late 2007.

The PALM-3000 system will have the unique capability of delivering a Strehl ratio of over 85% at K-band using a laser guide star. This gives a predicted contrast of 100,000:1 at separations greater than 0.4 arcsec from relatively faint ($m_V > 10$) stars using the Cornell-built PHARO coronagraph, already at Palomar. No other LGS AO system today can achieve this high Strehl ratio and contrast around faint stars. For example, Gemini ExAOC (expected in 2009), is intended to operate only on natural guide stars (NGS) brighter than about $m_V = 12$, whereas PALM-3000 will achieve high contrast on targets down to at least $m_V = 17$.

Compared to planet-finding instrumentation on larger diameter telescopes, PALM-3000 benefits from higher spatial bandwidth of correction. 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 system (Section 4) already obtains contrast comparable to the best ground-based measurements on larger telescopes[22].

3. DESIGN CONCEPT

To achieve the new research and educational capabilities described here, we propose to augment the existing 241 active actuator deformable mirror (DM) in our AO system with a new 3,217 active actuator DM, based upon innovative new manufacturing techniques developed by Xinetics, Inc. This central element in the PALM-3000 system is already fully funded through an SBIR award # NNG05CA21C. Additional design of key subsystem components critical to the successful exploitation of this extremely high-actuator-count deformable mirror remain to be completed in the system design phase of the project. These key subsystems include:

- A 62x62 subaperture wavefront sensor camera (also supporting a 31x31 subaperture mode for LGS).

- An optimized, tip/tilt/focus visible-light pyramid NGS wavefront sensor camera (needed for LGS operations, as lasers do not provide tip/tilt or slowly varying focus information) (Section 3.2).
- An infrared-light pyramid NGS wavefront sensor camera (needed for study of low-mass stars and objects embedded in dusty environs) (Section 3.3).
- A red-optimized deep-depletion CCD for use in a new integral field spectrograph to be used with the upgraded PALM-3000 system.

Based on our successful experience during previous AO system upgrades, we expect the PALM-3000 could be initially operational within 3 years, paced by the delivery time of the DM (24 months) and available funding.

Table 2. Comparison of current and upgraded adaptive optics systems. We have in possession a Shack-Hartmann low-order WFS but plan to upgrade this with both near-IR and visible wavelength pyramidal wavefront sensors.

System property	Current system PALM-241	Upgraded system PALM-3000
Deformable mirror(s)	Single 349 actuator (241 actively controlled)	349 actuator woofer (349 controlled) and 4,356 actuator tweeter (3,217 active)
High-order wavefront sensor	16x16 Shack-Hartmann	31x31 or 62x62 Shack-Hartmann
Detector	80 x 80 E2V CCD39	256 x 264 pixels pnCCD[23], MIT CCID-56, E2V CCD50, or similar
Subaperture sampling	2 x 2 pixels/subap	2 x 2 pixels/subap
Max frame rate	2 kHz	2 kHz
Read noise (full rate)	6.4 e- (measured)	~3 e- (extrapolation of vendor's measurement)
Low-order wavefront sensor(s)	Visible 3x3 Shack-Hartmann	Visible (and/or infrared) pyramid sensor
Detector(s)	80 x 80 E2V CCD39	80 x 80 E2V CCD39 (and/or HgCdTe array in rapid readout mode)
Subaperture sampling	6x6 pixels/subap	3x3 pixels/pupil image
Processors	4 DSPs on 1 VME board	24 FPGAs, 48 DSPs on 12 cPCI boards

3.1 Predicted Performance

The upgraded PALM-3000 adaptive optics system will provide N=63 deformable mirror actuator control across the diameter of the 5.1 m telescope, corresponding to a projected spacing of just 8.2 cm. Thus, PALM-3000 will have 86% greater actuator density than any current AO system[24], allowing unprecedented correction of astronomical images. This will allow diffraction-limited science across the visible band using bright natural guide stars, with all-sky reach and more modest performance using an upgraded sodium laser guide star. The Strehl ratio expected for this system in NGS mode is described in Table 3 while example error budgets for both NGS and LGS cases are shown in Table 4.

The benefits of the higher-order wavefront control to LGS operations are two-fold: a reduction of wavefront error and an increase in the precision of NGS tip-tilt and focus sensing. Although the PALM LGS system will be limited by focal anisoplanatism, other error terms in the LGS adaptive optics error budget will be reduced, including atmospheric fitting error. For LGS operation, PALM-3000 will employ an alternative lenslet array to sample the pupil with N=31 subapertures across the diameter. All 3,217 actuator will be driven despite this lower sensor sampling, via interpolation. Future upgrades to sodium laser power (to ~35W) at Palomar would allow us to take advantage of full N=62, without change to the AO system.

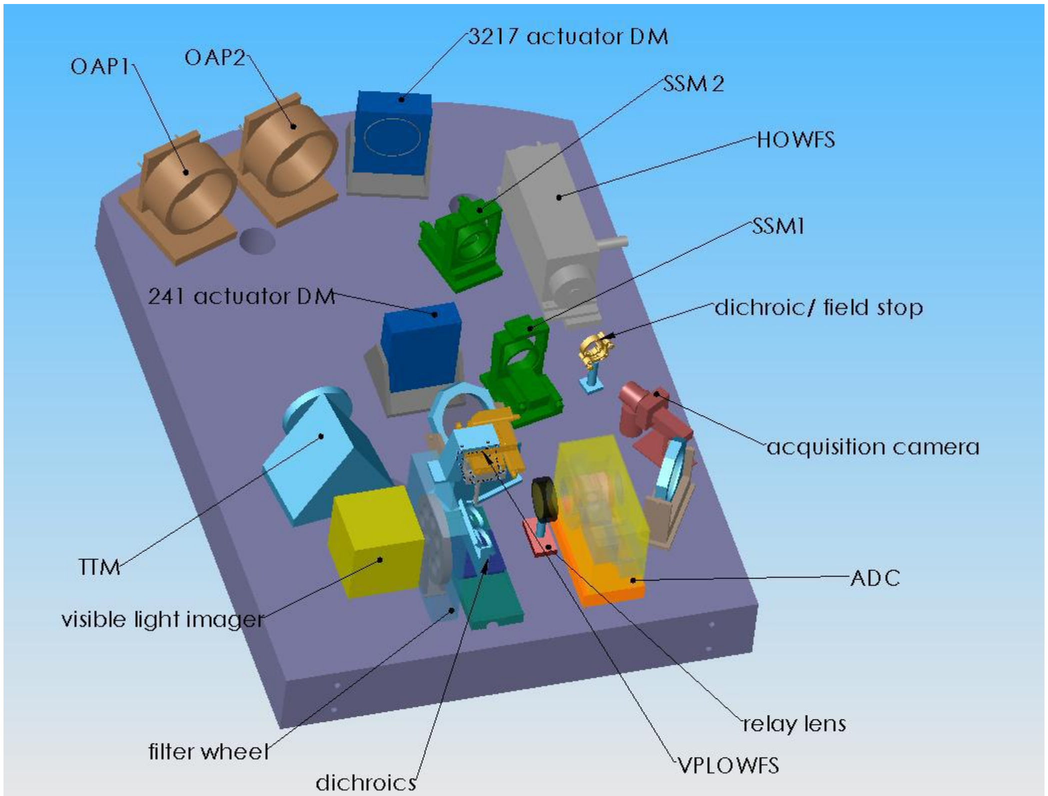

Figure 2. A rendering of one possible layout of the upgrade PALM-3000 adaptive optics system, configured for feeding a direct visible light imager. This configuration will also contain a filter wheel, an atmospheric dispersion corrector (ADC), the visible pyramid low-order wavefront sensor (VPLOWFS), and reimaging optics. Components highlighted in the existing PALM-241 system include a high-speed tip/tilt mirror (TTM), two guide star selection mirrors (SSMs), two 8" diameter relaying off-axis parabolas (OAPs). A dichroic picks off laser light for high-order sensing in the HOWFS. This configuration is similar to that needed for feeding the new visible-light IFU spectrograph, SWIFT, currently under construction at Oxford University for use behind Palomar adaptive optics. A separate configuration for infrared work will utilize our existing PHARO IR camera and the new infrared pyramid low-order wavefront sensor (IRPLOWFS).

Table 3. Expected Strehl ratio performance of PALM-3000 on bright *natural* guide stars, under various seeing conditions (described by Fried's parameter, r_0) typical of Palomar Mountain. In this table RMS WFE refers to the root-mean-squared residual wavefront error (in nanometers) delivered by the AO system and instrument to the science focal plane.

Seeing condition	r_0(0.5μm)	RMS WFE	On-axis Strehl Ratio for $m_V = 7$ star			
			0.4 μm	0.5 μm	0.7 μm	2.2 μm
Superior	25 cm	71 nm	29%	46%	67%	96%
Good	15 cm	84 nm	18%	33%	57%	94%
Median	10 cm	109 nm	5%	15%	38%	90%
Poor	5 cm	196 nm	--	--	5%	73%

Because PALM-3000 LGS will sharpen the natural guide stars used to provide tip/tilt and focus information, far more of these guide stars are available than for low-order AO systems. PALM-3000 will dramatically increase LGS sky coverage to be capable of using $m_v = 20$ or fainter NGS for tip/tilt correction. Even in regions of the sky devoid of bright guide stars (such as the GOODS fields), PALM-3000 will deliver improved Strehls in the near-infrared (Figure 3).

These improvements can only be realized by employing pyramid low-order NGS wavefront sensors, described further in Section 3.2 and 3.3.

3.2 Visible Pyramid-based Low-Order Wavefront Sensor (VPLOWFS)

When the high-order wavefront control is performed using a laser guide star, an NGS must still be used to determine global tip/tilt and focus. An NGS pyramid wavefront sensor[25] (PWFS) can take full advantage of the diffraction-limited starlight delivered by PALM-3000, while allowing the number of low-order modes sensed to be adjusted by binning the detector pixels. Unlike a Shack-Hartmann wavefront sensor, which segments the wavefront in the pupil plane, the pyramid sensor segments the light in a focal plane, largely eliminating subaperture diffraction effects. This approach has significantly better performance for precision ground-based adaptive optics systems than does a traditional 3x3 subaperture tip/tilt/focus sensors. We intend to characterize the performance of the NGS VPLOWFS in the lab (using fixturing previously developed for our tomographic wavefront sensor) before fielding it in PALM-3000.

Table 4. Example error budget for PALM-3000 using a bright natural guide star ($m_V = 7$); a planned 20W upgraded laser, and the current 8.5 W Chicago Sum Frequency Laser, in $r_0(0.5\mu m) = 15$ cm seeing conditions at Palomar Mountain. This corresponds to Strehl ratios of 57%, 23%, and 15% for the three cases, respectively, at an observing wavelength 0.7 μm. This level of performance is sufficient to conduct all of the science programs presented in Table 1.

Error source (all terms are in nm RMS)	**M_V=7 NGS** (62x62 subaps.)	**20 W LGS** (31x31 subaps.)	**8.5 W LGS** (31x31 subaps.)
Atmospheric fitting error, $r_0(0.5\mu m) = 15$ cm	26	46	46
Residual aliasing error	2	4	4
DM finite stroke error	3	3	3
Bandwidth error	44	48	71
Measurement error	46	52	75
Angular anisoplanatism error (on-axis)	0	0	0
Centroid anisoplanatism error	0	17	17
LGS focal anisoplanatism error	0	72	72
Chromatic error	2	2	2
Scintillation error	18	12	9
WFS zero-point calibration error	20	30	30
Uncorrectable AO system aberrations	15	20	25
Uncorrectable instrument aberrations	15	20	25
Uncorrectable telescope aberrations	30	45	45
Tip/Tilt equiv. meas. error (LGS: m_V=14; on-axis)	1	30	37
Tip/Tilt equiv. bandwidth error	14	29	28
Total wavefront error	**84**	**134**	**155**

3.3 Infrared Pyramid-based Wavefront Sensor (IRPLOWFS)

The VPLOWFS described above is the best low-order sensor for use with early spectral type natural guide stars. However, significant science advantage can be gained using infrared photons when guiding on low-mass stars, where spectral emission is peaked toward longer wavelengths. This is particularly true for our key program of mass/luminosity studies of pre-main sequence binaries, but has widespread application to our multi-user community, including targets deeply embedded in dust environments. With some targets suffering factors of 100 or more optical extinction in dusty regimes, the use of the IRPLOWFS is essential for delivered sensitivity in R-band (the penalty due to 5 mag extinction of our tip/tilt star is ~1% Strehl vs. 23% in the 20W LGS scenario described in Table 4). Thus, we also propose to construct an infrared version of the pyramid-based wavefront sensor, using the lessons learned with the VPLOWFS for greatest efficiency in construction. Leveraging an earlier investment to Rockwell Scientific for the development of next-generation small-format, low-noise HgCdTe detectors, we are already in possession of one option for the necessary detector array. At the same time, we are considering other alternatives, such as the rapid readout of commercial science-grade HgCdTe arrays such as the Raytheon VIRGO and Rockwell HAWAII-2RG arrays.

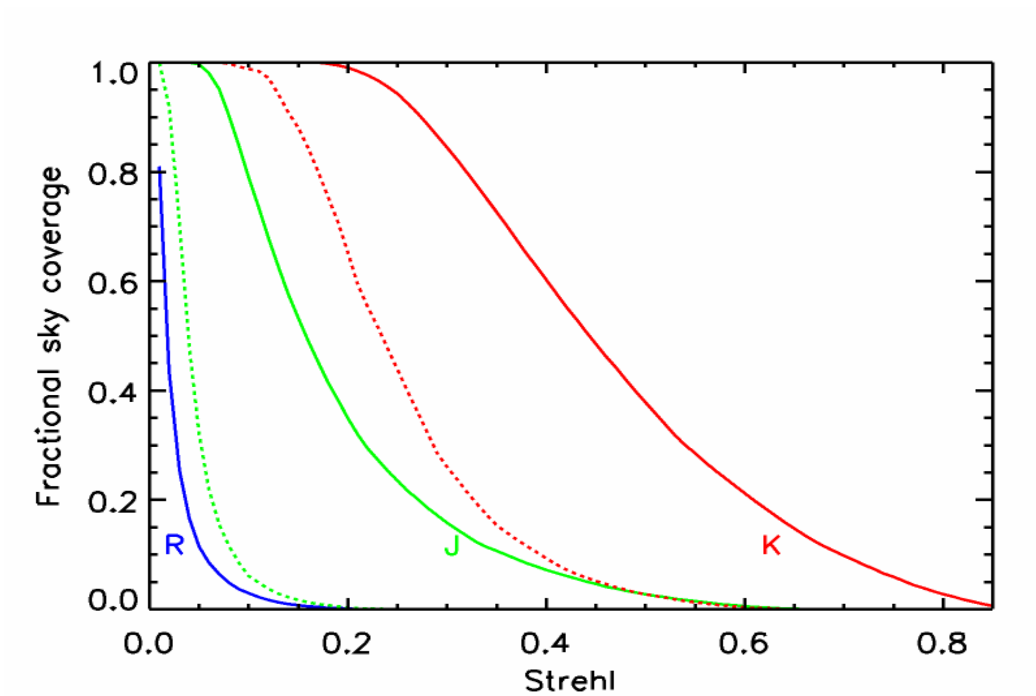

Figure 3. Sky coverage for PALM-3000 (*solid lines*) compared to PALM-241 (*dashed lines*) as a function of the Strehl achieved in R (0.64 µm, *blue*), J (1.25 µm, *green*), and K (2.15µm, *red*) bands, in $r_0(0.5\mu m)$ = 15 cm seeing conditions. In addition to accessing visible bands, PALM-3000 will dramatically improve the workhorse J, H, K infrared band science currently conducted at Palomar.

3.4 Red-Optimized Deep Depletion CCD for Visible Science

To fully capitalize on the unique potential of PALM-3000 we have entered into collaboration with Oxford University for the development of an optimized visible instrument for use with the PALM-3000 system. This 44 x 89 spatial element integral field spectrograph will provide spectral resolution of 3,500, covering the wavefront range 656 nm to 1050 nm. Caltech's commitment to this collaboration includes a deep-depletion charge coupled device (CCD) detector, of dimension at least 4k x 2k with a goal of 4k x 4k pixels. These devices will be available in the planned period from Lawrence Berkeley Labs (LBL), E2V, Fairchild or Hamamatsu, at comparable costs.

4. EXISTING AO SYSTEM STATUS

The original Palomar AO system, PALM-241, is currently a world-class natural guide star (NGS) AO system achieving wavefront errors as low as 170 nm rms in 0.5 arcsec visible seeing and 190 nm rms in 0.9 arcsec visible seeing. This corresponds to a scientific K-band imaging Strehl ratio of 80%, higher than reported for AO systems at Keck, Gemini North, and nearly all other non-DoD adaptive optics systems. The outstanding image compensation of PALM-241 at infrared wavelengths recovering at least 6 Airy rings is shown in Figure 4. The real-time control computer within PALM-241, designed by current team members, is among the fastest anywhere in the world, with top frame rates of 2 kHz and extensive telemetry recording capability (up to 400 Hz continuous telemetry recording, all night). PALM-241 represents an approximately $7M investment (program life cycle cost 1995 to date), which provides the platform and infrastructure to enable cost-effective implementation of the visible-light AO system upgrade.

5. CONCLUSIONS

As the first operational visible-light astronomical AO system, PALM-3000 will draw a new generation of young researchers into the field of high-angular-resolution astronomy inspiring students to explore a new frontier that will be inaccessible at any other facility. Young people are naturally drawn to the high-resolution astronomy by the visual impact of beautiful images and the state-of-the-art technologies employed in adaptive optics, which are seen as building blocks for their further technical education. Our field provides natural tools with which we can reach out to interest young people, including underrepresented minorities. We look forward to creating a unique resource for our national academic research infrastructure and blazing the trail for follow-on visible-light AO projects on 8-10m telescopes coming in the decade of the 2010's.

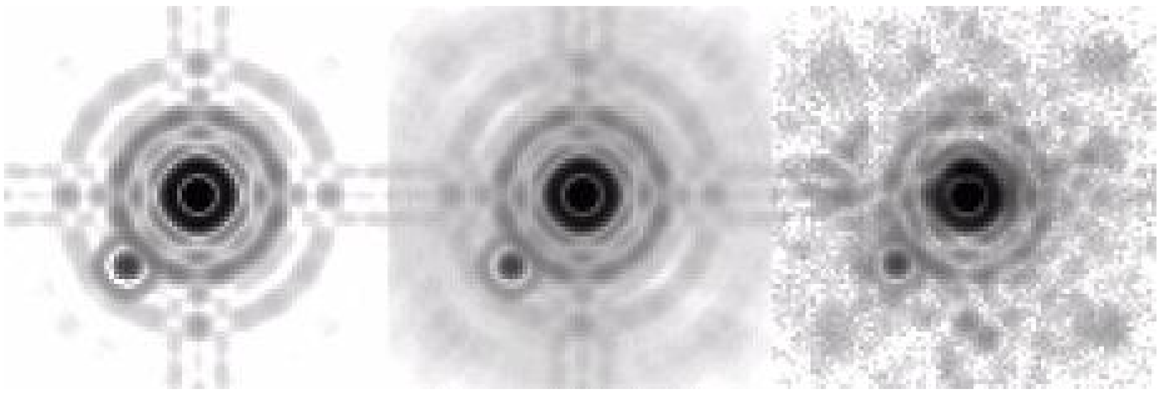

Figure 4. Comparison between a theoretically perfect multispectral point spread function (PSF) (Left), results from closed-loop Monte Carlo simulations (Center), and (unprocessed) data from a PALM-241 observation (Right) obtained September 2003 guiding on an $m_V = 7$ star in 0.9 arcsec visible seeing ($r_0 = 11$ cm). The measured wavefront error is about 190 nm rms (73% Strehl). ($\lambda = 2.145$ μm, $t_{exp} = 5$ seconds). The numerical simulations include the effects of a 1% ghost reflection in the PHARO camera (lower left of image).

ACKNOWLEDGMENTS

Support for the real-time reconstruction computer for PALM-3000 has been provided by the Air Force Office of Sponsored Research, Award #FA9550-06-1-0343 (DURIP FY06). Support for the PALM-3000 662 actuator DM is provided by SBIR award # NNG05CA21C. Upgrades to the Chicago Sum Frequency Laser have been funded in part by the Center for Adaptive Optics under the STC Program of the National Science Foundation, Agreement No. AST-98-76783. Generous support for the adaptive optics interface to the Oxford SWIFT instrument has been provided by Ron and Glo Helin.

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