3 PROJECT DESCRIPTION

3.1 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 propose to develop the first *visible* light sodium laser-guide-star astronomical adaptive optics system, PALM-3000, to be deployed as a multi-user shared facility on the 5.1 meter Hale Telescope at Palomar Mountain. This represents a state-of-the-art instrument upgrade, building on the existing successful near-infrared Palomar AO system. Specifically PALM-3000 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[i] 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.

We request MRI support for instrument development of PALM-3000, allowing us to fully exploit our new 3,217 active actuator DM (funded elsewhere). This includes supporting the construction of two new optimized wavefront sensors, a large-format red-optimized CCD for use for visible science, and integration and commissioning costs for this multi-user facility. This will enable entirely new diffraction-limited visible-light science unobtainable with any other instrument.

3.2 Research Activities

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.

3.2.1 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).

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

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 HST work in the infrared[7,8,9,10,11,12,13,14] extend inward only to tens of AU, limiting the constraint of models.

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	62	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	62	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	62	94	2.2	3% precision for dozens of stars to faintness mK = 22
Hot, young exo-Jupiter study	NGS / < 6	object itself	62	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

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. In all cases N=64 actuators are used for static correction of telescope and instrument aberrations. 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 $r_0(0.5\mu)$ = 15 cm.

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 so 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.

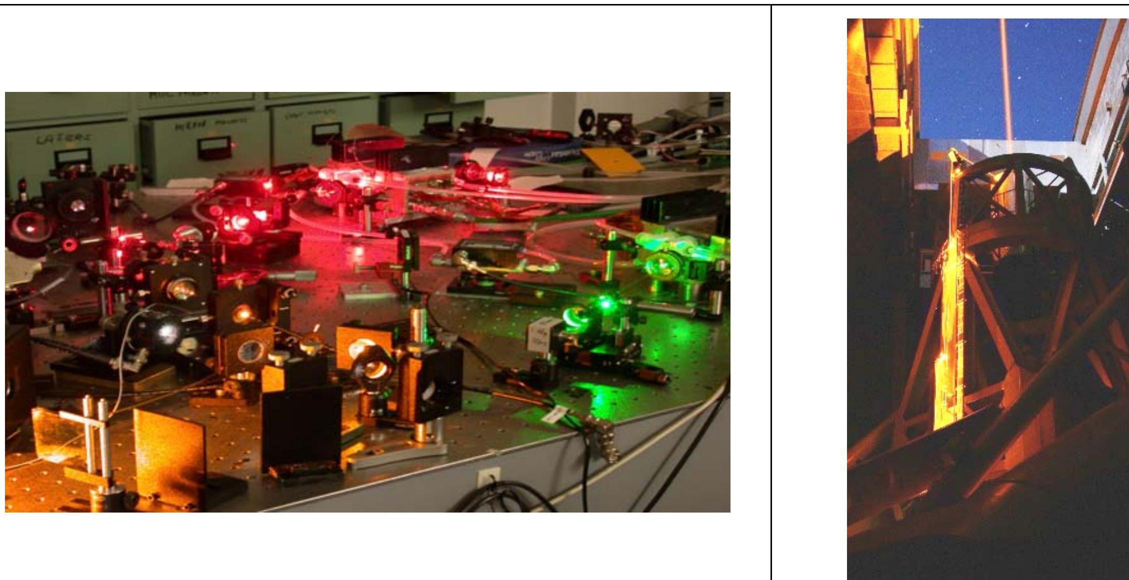

Figure 1. **(Left)** The successful 8.5W Chicago Sum-Frequency Laser (CSFL), showing yellow sodium 589nm light generation. **(Right)** Initial projection of the CSFL at Palomar Observatory (Oct. 2004). The laser resides in the Coude lab and is projected along a servo mirror system to a 50 cm diameter 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.

3.2.2 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 the 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.

3.2.3 Direct Detection of Hot, Young Exo-Jupiters

Since the discovery of the first substellar object at Palomar Observatory in 1995[18], 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.

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 3.3.6) already obtains contrast comparable to the best ground-based measurements on larger telescopes[22].

3.2.4 Results from prior NSF support

The Principal Investigator, Dr. Richard Dekany, has previously received instrument support through NSF Grant AST-0096928, totaling $299,678, for the construction of a 4-channel Shack-Hartmann wavefront sensor to be incorporated into the Palomar Adaptive Optics System (Figure 2). This system allows "tomographic" wavefront sensing of the atmosphere using natural asterisms to experimentally verify multiconjugate adaptive optics simulations.

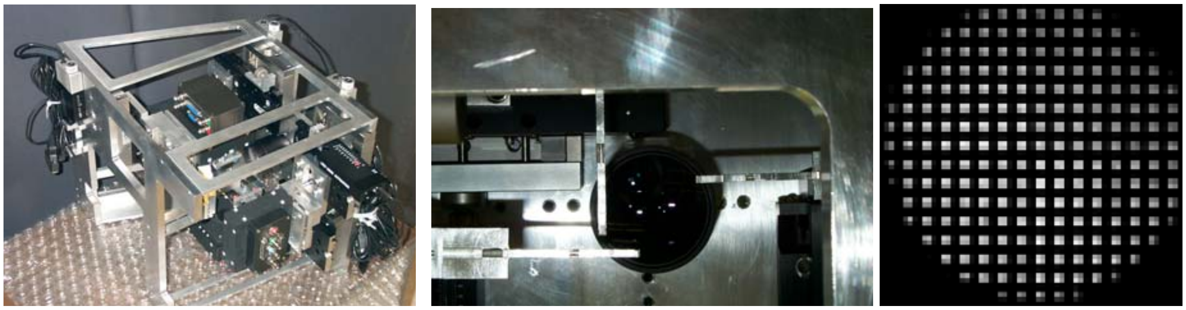

Figure 2. Tomograph hardware (**Left**) of the four channel tomographic wavefront sensor funded under AST-0096928. Four fast-frame, low-noise CCD cameras (each mounted on its own x-y positioning stages) are arranged symmetrically around a patrol field of 90 arcsec diameter. Optics on small (1.5mm) pick-off arms (**Center**) form 16x16 subaperture Shack-Hartmann images **(Right)**.

Successful experiments with the Palomar Tomograph have produced first-of-its-kind high-order, high-temporal bandwidth wavefront information, with several research publications now in preparation. The PI has opened disseminating research collaborations with Dr. Ralf Flicker, of Keck Observatory, and Mr. Lianqi Wang, a University of California, Irvine gradate student who will be conducting Ph.D. dissertation work on atmospheric characterization using our 4-channel wavefront sensor data.

3.3 Research Instrumentation and Needs

3.3.1 PALM-3000 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, and we request here support for the design and construction of components critical to exploiting this extremely high-actuator-count deformable mirror, including:

- A 62x62 subaperture (256x264 pixel) wavefront sensor camera (funded elsewhere).
- 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 3.3.3).
- An infrared-light pyramid NGS wavefront sensor camera (needed for study of low-mass stars and objects embedded in dusty environs) (Section 3.3.4).
- A red-optimized deep-depletion CCD for use in a new integral field spectrograph to be used with the upgraded PALM-3000 system (Section 3.3.5).

The upgrades for which we are here requesting funding are described in more detail and given context in subsequent sections (see the Work Breakdown Structure in Section 3.5.1). Based on our successful integrated product team development method used during previous AO system upgrades, we expect the PALM-3000 to be initially operational within 3 years, paced by the delivery time of the DM (24 months).

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
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 (infrared) pyramid sensor
Detector(s)	80 x 80 E2V CCD39	80 x 80 E2V CCD39 (RSC HgCdTe "Calico" MUX")
Subaperture sampling	6x6 pixels/subap	3x3 pixels/pupil image
Processors	4 DSPs on 1 VME board	24 FPGAs, 48 DSPs on 12 cPCI boards

Table 2. Comparison of current and upgraded adaptive optics systems. The upgraded high-order wavefront sensor baseline camera is a pnCCD detector[23] produced by PNSensor GmbH (funded elsewhere).

3.3.2 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.

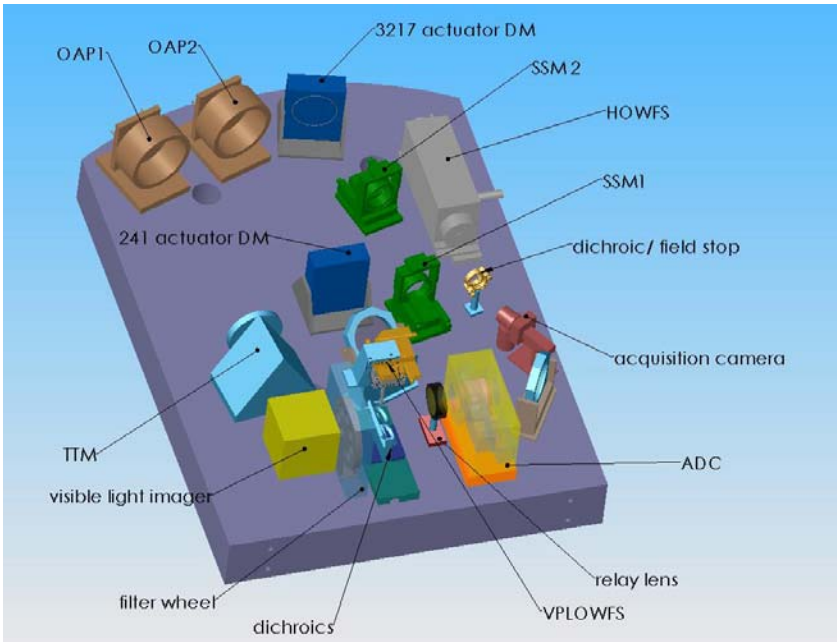

Figure 3. A rendering of the upgrade PALM-3000 adaptive optics system in a configuration feeding a direct visible light imager. This configuration will also contain a filter wheel, an atmospheric dispersion corrector (ADC), the visible pyramid low-order wavefront sensor (VPLOWFS), and reimaging optics. 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 under construction at Oxford University for use at Palomar. A separate configuration for infrared work will utilize our existing PHARO IR camera and the new infrared pyramid low-order wavefront sensor (IRPLOWFS).

Seeing condition	$r_0(0.5\mu m)$	RMS WFE	On-axis Strehl Ratio for $m_V = 7$ star			
			0.4 micron	0.5 micron	0.7 micron	2.2 micron
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%

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.

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.

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 4). These improvements can only be realized by employing pyramid low-order NGS wavefront sensors, described further in Section 3.3.3.

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**

Table 4. Example error budget for PALM-3000 using a bright natural guide star ($m_V = 7$); a planned 20W upgraded laser (funded elsewhere), 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.

3.3.3 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.

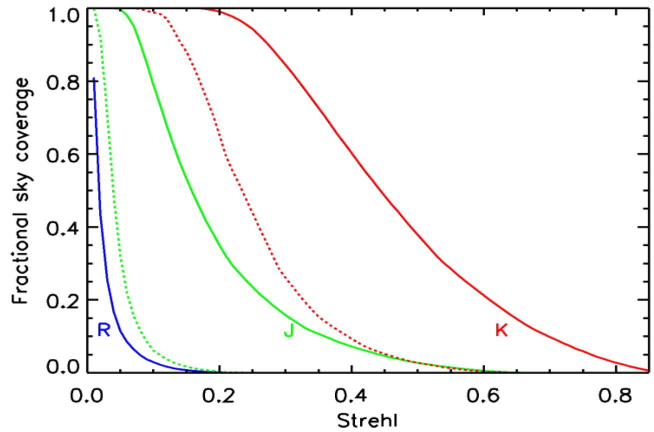

Figure 4. Sky coverage for PALM-3000 (*solid lines*) compared to PALM-241 (*dashed lines*) as a function of the Strehl achieved in R (0.64 µm, *blue*), J (1.25 µm, *green*), and K (2.15µm, *red*) bands, in r_0(0.5µm) = 15 cm seeing conditions. In addition to accessing visible bands, PALM-3000 will dramatically improve the workhorse J, H, K infrared band science currently conducted at Palomar.

3.3.4 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 the necessary detector array. We request here funding for the construction of a complete nitrogen cryostat and camera integration and testing.

3.3.5 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. Oxford University has obtained (£1.5M) funding for their share of this collaboration from a Marie Curie Fund grant from the European Union, making this a highly leveraged investment. 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. As a key component of the visible camera to exploit PALM-3000, we request funding for this device from the MRI program.

3.3.6 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 5. 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.

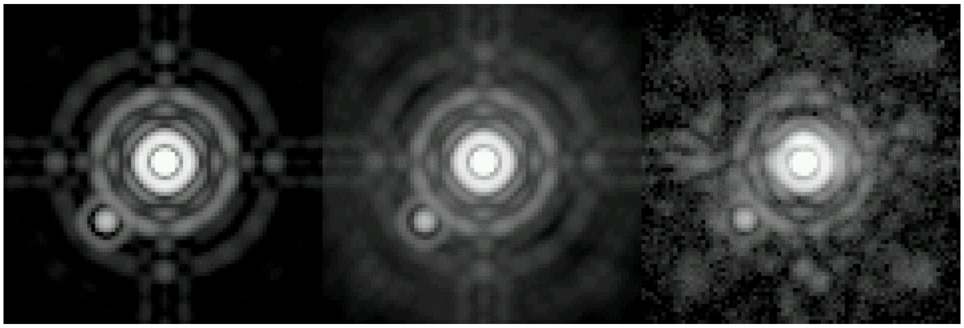

Figure 5. Comparison between a theoretically perfect multispectral point spread function (PSF) (**Left**), results from closed-loop Monte Carlo simulations (**Center**), and (unprocessed) data from a PALM-241 observation (**Right**) obtained September 2003 guiding on an $m_V = 7$ star in 0.9 arcsec visible seeing (r_0 = 11 cm). The measured wavefront error is about 190 nm rms (73% Strehl). (λ = 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).

3.4 Impact of PALM-3000 Instrument Development

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. The project will create a unique resource for our national academic research infrastructure and blaze the trail for follow-on projects on 8-10m telescopes in the decade of the 2010's.

3.4.1 Undergraduate Education

The Palomar AO team has demonstrated a strong commitment to student education, training students to be leaders in adaptive optics, astronomy, and physics, as summarized in Table 5. In our group, both graduate and undergraduate students learn through inquiry, helping senior researchers identify questions fundamental to both the astronomy and the engineering that we undertake. Student participation is organized around research projects that they help identify, take ownership of, and frequently publish. For example, 2005 undergraduate Mark Eichenlaub became interested in understanding the 3-dimensional structure of turbulence in the atmosphere. With guidance, he formulated a set of questions regarding image point spread function uniformity across the AO-compensated field. He turned this into a formal experiment plan which he executed during 4 nights on our system at Palomar Mountain. Based on his results, which were initially confusing, he revised the experiment to control additional parameters (e.g. star multiplicity) and repeated the experiment (of his own initiative, after this fellowship had formally ended), exercising the process and building the habit of continual learning.

The PALM-3000 collaboration is specifically interested in targeting undergraduate education to encourage promising students to continue into graduate programs emphasizing science and technology, where the national need is acute. As an integral part of this work, the team is committed to mentoring six (6) Summer Undergraduate Research Fellowship (SURF/MURF) positions at Caltech. This highly successful program brings in undergraduates from around the United States for 10 weeks of guided research alongside a diverse peer group. The SURF program at Caltech typically supports over 100 students each year. Through Caltech's MURF program, which provides additional resources to promote a culturally and socioeconomically diverse SURF program, our group has in the past successfully recruited promising students from diverse cultural and socioeconomic backgrounds. In fact, one of us, Prof. Scott Teare, currently involves 4 underrepresented minorities in his group of 8 undergraduate researchers.

To foster the continuing identification of promising underrepresented researchers, the PI will personally attend the Joint Annual Conference of the National Society of Black Physicists and Black Physics Students and the National Society of Hispanic Physicists, in San Jose, California on 15-19 February 2006. With the assistance of Ms. Lisa Hunter, Associate Director for Education at the NSF Science and Technology Center for Adaptive Optics (CfAO), the PI will join the CfAO delegation presenting at and participating in this unique forum which brings together over 500 students and professionals in a highly motivational setting.

Student	Advisor[i]	Institution	Status	Year	Current position
James Larkin	EK	U Chicago	P-Doc	1997	Professor, Astronomy, UCLA
Mark Chun	EK	U Chicago	Ph.D	1997	Asst. Professor, Astronomy, U of Hawaii
Mike Smutko	EK	U Chicago	Ph.D	1998	Lecturer, Astronomy, Northwestern University
Ben Oppenheimer	RD	Caltech	Ph.D.	1999	Asst. Curator, American Museum of Nat. Hist.
Barbara Carter	EK	Harvard	Ph.D	2001	Began Astronomy Ph.D. at Chicago 1995
					Transferred to Harvard University in 1997
Christoph Baranec	RD	Caltech	B.S.	2001	Ph.D, Optical Sci., U of Arizona, exp. 2007
Fang Shi	EK	U Chicago	Ph. D	2001	Senior Engineer, Jet Propulsion Laboratory
Jason Marshall	RD	UCLA	B.S.	2002	Ph.D., Astronomy, Cornell University exp. 2008
Christina Pelzer	MT	FIT	UG	2002	B.S., Physics, Florida Institute of Tech. exp 2005
Ben Matthews	RD	Caltech	B.S.	2002	B.S., Honors, Physics, 2004
Sara Salha	RD	UCLA	UG	2003	B.S., Physics, exp. 2005
Matthew Smith	MT	Harvard	UG	2004	B.S., Physics, exp. 2007
Stanimir Metchev	RD	Caltech	Grad	2004-	Ph.D., Astronomy, 2005 (Post-Doc, UCLA)
Mark Eichenlaub	RD	Caltech	UG	2005-	B.S. Physics, exp. 2007

Table 5. Student researchers supervised by the proposing research group. Among these former and current students are three women and one student belonging to an underrepresented minority.

3.4.2 Dissemination and Public Outreach

The PI will encourage community-wide access to PALM-3000 through multi-lateral science and AO research collaborations. Communications to the astronomical and AO technical communities will be maintained informally by the PI (a member of CfAO, an alumnus of University of Arizona, and current Caltech representative to the national University Space Research Association (USRA)) and by the Science Team, who hold a variety of Science Working Group (SWG), institutional board, and advisory positions across ground and space-based astronomy. More formal written dissemination will be made through articles and conferences related to technical progress and lessons learned will be reported via the publications of Astronomical Society of the Pacific (PASP), Optical Society of America (Applied Optics), the American Astronomical Society (AAS), Division of Planetary Science (DPS), and SPIE. This close integration of the broad US and international science communities will help ensure the rapid and effective

[i] EK = Kibblewhite, RD = Dekany, MT = Mitchell Troy (JPL)

dissemination of important lessons learned in deploying this first 5-10m class visible AO system. This will accelerate the adoption of visible-light AO as stock-in-trade for 8-10m astronomical observatories in the 2010's.

Dissemination of results to the broader public, including interpretation of sciences discovery and its impact on society, will be made to the public via Palomar Observatories new Visitor's Center (completion 2007) under the supervision of Palomar Observatory's Director of Public Relations, Mr. Scott Kardel. Palomar Observatory draws one hundred thousand visitors annually and we look forward to expanding our educational and outreach activities with this wonderful new facility. Mr. Kardel will spend approximately 25% of his time on PALM-3000 education and public outreach in Southern California, including lecturing throughout rural San Diego County secondary schools and community colleges. He will create a web-based kiosk presentation/display highlighting the science potential and results of visible adaptive optics for display in the Palomar Visitor Center and available on the web, for display in local planetaria and freely distributed in conjunction with school group presentations.

3.4.3 Multi-User Access

Access to the facility PALM-3000 system spans the nation, both geographically and in terms of researcher career level. Formal access is available to the entire research communities of Caltech, Infrared Processing and Analysis Center (IPAC), Cornell University, Jet Propulsion Laboratory, Oxford University, and to specific collaborators and their students at University of Chicago, American Museum of Natural History, University of California, and New Mexico Tech, through a competitive peer review proposal process conducted every six months. Although the theoretical applicant pool for PALM-3000 numbers in the thousands, more realistically we can estimate the pool of eligible, active users as the sum of the number of students and researchers within the relevant academic departments (astronomy, planetary science, and physics) of each partner institution plus our science team collaborators.

	Institution	Senior Personnel	Postdoctoral Scholars	Graduate Students	Undergrad Students
Eligible to Apply for Time	Caltech	35	50	60	45
	Cornell	12	20	25	50
	Jet Propulsion Laboratory	100	50	50	20
	University of Chicago	1	2	5	5
	Oxford University	10	10	20	50
Collaborators	American Museum of Natural History	3	2	2	1
	University of California	3	6	10	5
	New Mexico Tech	1	3	3	8
	Total Multi-Institutional Access	**165**	**143**	**175**	**184**

Table 6. User Access to the PALM-3000 Upgrade (membership of astronomy, planetary science, and physics departments eligible to apply or co-apply for time allocation via peer review)

3.5 Project Management Plan

3.5.1 Work Breakdown Structure

The development of a visible-light adaptive optics system on a 5.1 meter diameter ground-based telescope is an ambitious goal, but reachable and cost-effective when implemented as an upgrade to an existing state-of-the-art AO system working well at infrared wavelengths. The total budget for the PALM-3000 development, including all visible science instrument interfaces, is $6,253,000. Approximately 55% of this cost is due to professional and student labor, for which significant existing support is available. Caltech Optical Observatories has committed 2.5 full-time equivalent staff support from its on-going operations budget (equivalent to $1,640,000 over 4 years). As a 37.5% observing share partner in Palomar Observatory, Jet Propulsion Laboratory also contributes engineering labor (approximately $1,320,000 over 4 years). Hardware support is provided for the 3,217 actuator deformable mirror through funded SBIR #NNG05CA21C ($800,000). Center for Adaptive Optics funding for upgrades to our sodium laser guide star (from 8.5W to 20W of power) is funded in the current year (approx. $100,000). Additional, hardware support has been requested from the NSF ATI program ($1,029,000) and the Department of Defense DURIP program ($250,000).

We are requesting from the MRI program $1,114,000 for PALM-3000 project elements, distinct from all other sources, in order to complete our funding profile and realize this exciting program. Most notably we request here support for visible-light instrument costs not requested elsewhere. The product-based Work Breakdown Structure (WBS) for the full PALM-3000 instrument development is shown in Figure 6. The corresponding full project schedule and our specific MRI funding request, organized by WBS element is shown in Figure 7.

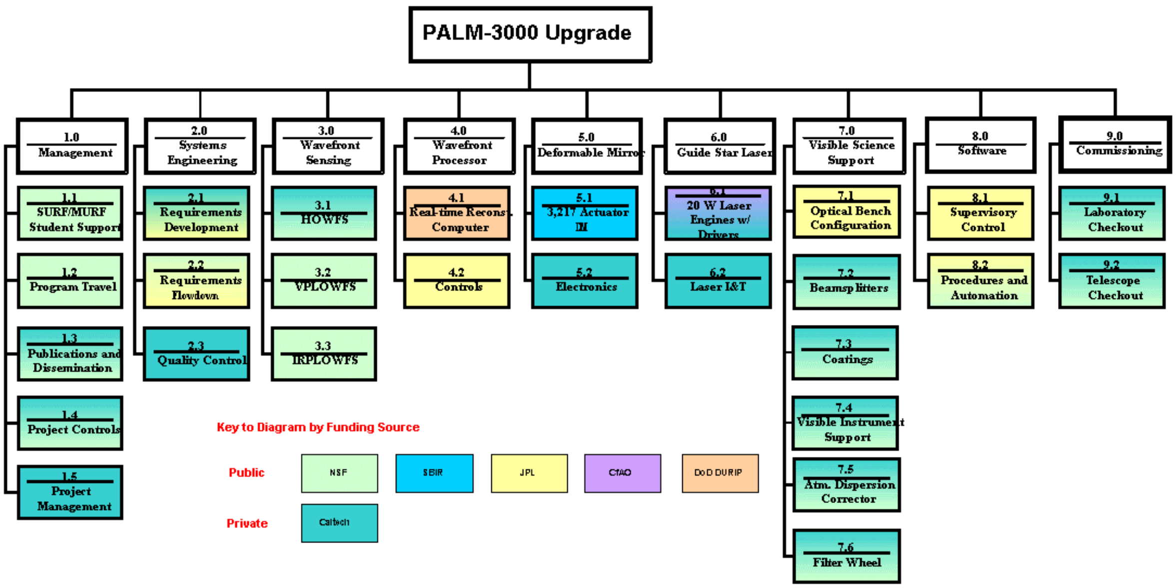

Figure 6. PALM-3000 Work Breakdown Structure. Funding sources for this public/private partnership are indicated by color. Caltech, JPL, SBIR, and CfAO funds are in hand, while DoD DURIP and NSF funding is proposed. Where more than 20% of funding is multi-sourced, multiple colors are indicated.

3.5.2 Major Project Milestones (and corresponding major *Deliverables)*

In Year One of the three-year effort, we will:

1. Refine the PALM-3000 science case and generate formal functional requirements documentation *(Management Plan, Function Requirements Document, Software Requirements Document, Risk Mitigation Plan, Optical Bench Interface Control Document)*
2. Select a VPLOWFS camera vendor, construct the VPLOWFS *(VPLOWFS Design Document)*
3. Place real-time computer hardware order near the end of Year One *(RTC Design Document)*

In Year Two, we will:

4. Select a HOWFS camera vendor, construct the HOWFS *(HOWFS Design Document)*

5. Hold a Preliminary Design Review *(PDR Documentation, Updated Risk Mitigation Plan)*
6. Perform detailed design and assembly of the IRPLOWFS *(IRPLOWFS Design Document)*
7. Program and benchmark the real-time controller (RTC) *(RTC Performance Report)*

In Year Three, we will:

8. Receive 3,217 actuator Xinetics, Inc. deformable mirror (DM)
9. Hold a Detailed Design Review *(DDR Documentation, Updated Risk Mitigation Plan)*
10. Calibrate the 3,217 actuator DM and electronics *(DM Calibration Report)*
11. Calibrate HOWFS, VPLOWFS, and IRPLOWFS *(HOWFS, VPLOWFS, and IRPLOWFS Calibration Reports)*
12. Verify HOWFS data interface to RTC in laboratory tests

In Year Four, we will:

13. Hold a Pre-Ship Design Review *(PSR Documentation, Updated Risk Mitigation Plan)*
14. Install the 3,217 actuator DM in the AO system (moving the 241 actuator DM)
15. Install VPLOWFS, IRPLOWFS, and HOWFS and verify in lab *(Technical Project Final Report)*
16. Perform first natural guide star (NGS) tests with PALM-3000 *(User Documentation)*
17. Perform first laser guide star tests with PALM-3000 (~4 months after NGS tests) *(Updated User Documentation)*

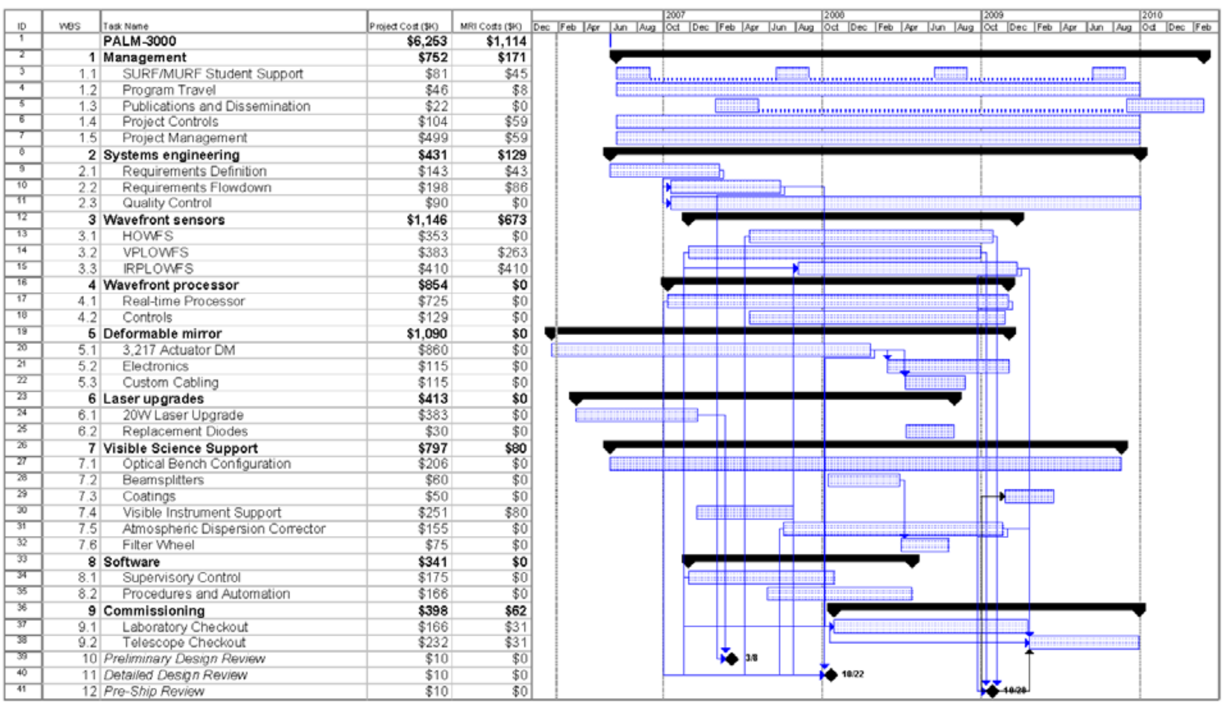

Figure 7. PALM-3000 project schedule overview by WBS element. The major milestones and deliverables addressed in this proposal are summarized in Section 3.5.2.

3.5.3 Risk Mitigation and Controls

The PI will use probably/impact analysis to develop a formal Risk Management Plan (RMP), using techniques such as Root Cause Identification and stakeholder Interviewing. Identification of key design challenges will occur at formal Preliminary, Detailed, and Pre-Ship project reviews wherein the RMP will be updated. Currently, we have identified the highest risk items of an initial Risk Register and propose potential mitigation strategies in Table 7.

A key technical systems engineering tool for tracking and controlling science performance risk is the maintenance of a comprehensive performance error budget, such as shown in Table 4. As various system components proceed through laboratory characterization, actual performance numbers will be substituted into the design error budget, allowing us to rebalance the allocation of errors between subsystems. Programmatic risks will be managed using detailed financial and schedule tracking basis of Earned Value (EV) analysis[26], the standard approach used in Caltech's instrument development group.

Event	Likelihood	Impact	Mitigation
Late delivery of the 3,217 actuator DM	Moderate	High; On schedule critical path; postpones initial sky tests; increases project cost	The project budget includes travel for quarterly status meetings at the Xinetics facility to provide early warning of schedule slipage. To contain costs of a holding delay, staff can be shifted to other Caltech projects.
Poor understanding of atmospheric conditions at Palomar	Moderate	Moderate; Performance below expectations	We are currently conducted routine evaluation of $C_n^2(h)$ and seeing using a dedicated MASS/DIMM instrument at Palomar. Longer baseline seeing measurements will inform the design process leading up to the Detailed Design Review.
Late delivery of the visible science camera deep depletion CCD	High	Low; currently this item is well outside the critical path	We are delaying the procurement of this device to FY08 to allow vendors to continue to mature their technologies (already commercially offered). We will continue close communication with vendors to maintain insight into delivery times.

Table 7. Currently identified areas of high risk. A formal Risk Mitigation Plan is an early management deliverable of the project.

3.5.4 Organization

Responsibility for the successful completion of this project resides with Dr. Richard Dekany, the Principal Investigator. The PI has successfully managed similar complexity as PI for the initial PALM-241 instrument development, begun in 1995 as one of the first large telescope facility AO projects. Recognizing the unique challenges for achieving visible light AO performance, subsystem development will be carried out in several Integrated Product Teams (IPTs) organized around the major functional components.

Undergraduate researchers in Caltech's SURF/MURF program will work alongside professional astronomers and engineers, rarely in the critical path but often within sight of it. Exact involvement within our IPT structure is made by structuring student-motivated inquiry and skill sets into specific projects, often associated with more deeply understanding the physical processes at work in the Earth's atmosphere or in characterizing our equipment (such as detector arrays) during instrument development.

The PI has assembled a strong volunteer science team that has already contributed to the planning and requirements flow-down for this upgrade, and an expert technical team for the execution of the work plan. The role of the Science Team is to advise the PI on design and other matters affecting science utility of PALM-3000. To this end, Science Team members will actively participate in:

- Development of operational concepts for PALM-3000 use, addressing such tradeoffs as photon-sharing balance between wavefront sensors (performance) and science instrument (sensitivity)
- Science requirements flow-down into wavefront error budget allocation
- Execution of 'validation' science programs made during PALM-3000 I&T and dissemination of experience from these early science programs to the IPTs and to the national astronomy community

The technical team has broad previous adaptive optics engineering experience which is essential in successfully realizing an AO system that can perform at visible wavelength. PALM-3000 team members have constructed visible-light NGS AO system on the Mt. Wilson 2.5m diameter telescope, made extensive use of the visible-light NGS AEOS system on Haleakala, HI, and conducted successful visible-light NGS tests on a 1.5m telescope subaperture at Palomar. Sodium LGS experience is deep and include design and use of LGS systems at Apache Point, NM, Keck Observatory, HI, and Palomar Mountain.

This proposal will specifically fund Dr. Bouchez, whose experience includes AO engineering of the Keck LGS AO system, Mr. Velur, an optomechanical engineer who has built 4 previous wavefront sensors while at Caltech, and Mr. Smith, our chief infrared detector engineer. This experience is essential to optimizing the instrument transmission, correction performance, and operational efficiency.

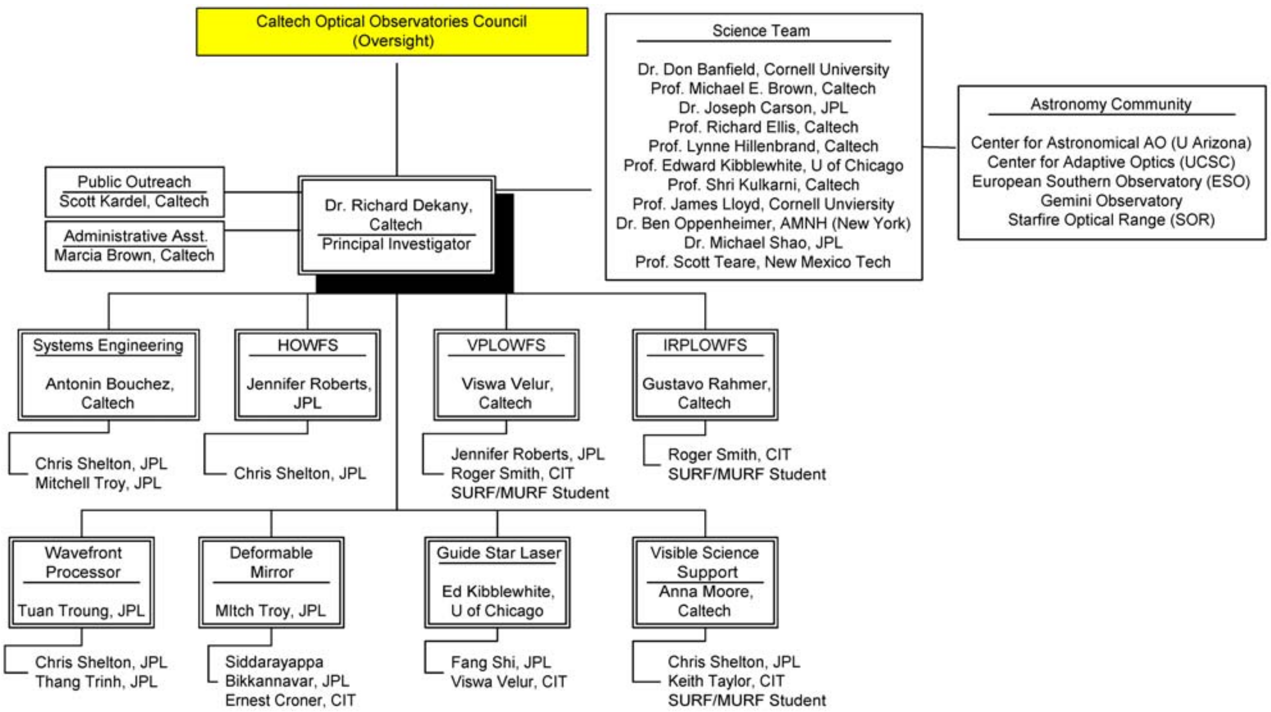

Figure 8. Full PALM-3000 Organization by Integrated Product Team (IPT). SURF/MURF students will participate embedded within small engineering teams, conducting stand-alone hands-on research projects.