Extreme Adaptive Optics Coronagraph (ExAOC) Design Study

A proposal to AURA and the Gemini Observatory

by the NSF Center for Adaptive Optics at UC Santa Cruz

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Executive Summary

For the first time in history, direct and indirect detection techniques have permitted astronomers to explore the environments of nearby stars on scales comparable to the size of our solar system. Exploitation of precision Doppler measurements has led to the discovery of the first extrasolar planets, while high-contrast imaging has revealed new classes of objects including dusty circumstellar debris disks and brown dwarfs. These discoveries have galvanized public interest in science and technology and have led to profound new insights into the formation and evolution of planetary systems, and they have set the stage for the next steps: direct detection and characterization of extrasolar Jovian planets.

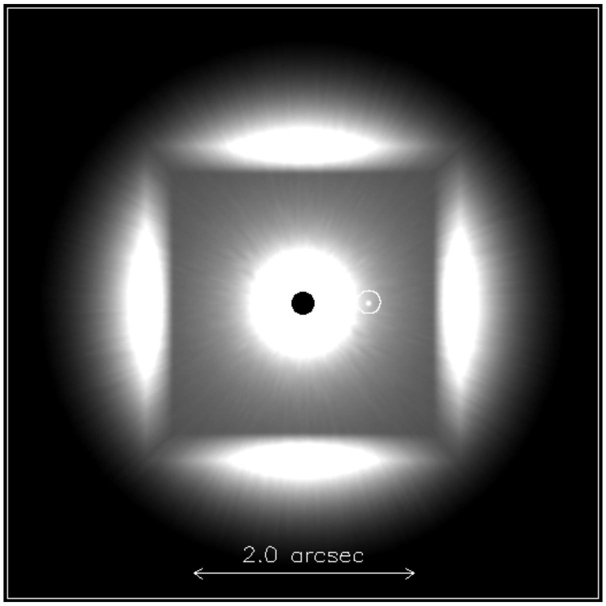


Figure 1: Simulated 450 second ExAOC integration showing a 8 Jupiter-mass extrasolar planet in a 5 AU orbit around a solar-type star at 10 pc. The star is located behind an occulting spot. The square "dark hole" region, 2.6" on a side, is produced by our spatially-filtered wavefront sensor (SFWFS). This is a direct broadband image with no post-processing.

The NSF Center for Adaptive Optics (CfAO) has been one of the major players in the new field of "Extreme" adaptive optics (ExAO). In response to the Gemini RFP, the CfAO has formed the best possible partnership to produce an ExAO instrument. In addition to our core CfAO members – LLNL, UCSC, UC Berkeley, and JPL – our team includes as a major partner the Herzberg Institute of Astrophysics group who delivered Altair, perhaps the world's most sophisticated AO system, to Gemini. The collaboration also includes the University of Montreal group that invented the concept of differential multi-wavelength imaging for AO, together with the UCLA infrared instrumentation laboratory, the American Museum of Natural History Lyot Project team, and the world's leading manufacturer of MEMS deformable mirrors. Our project scientist, James Graham, has assembled a world-class science team to guide our effort.

Our team has produced a system design incorporating a spatially-filtered wavefront sensor that allows precise control of mid-frequency aberrations that scatter light over the 0.1-1.3" range. By removing these phase errors we can produce a PSF with a characteristic "dark hole" (Figure 1). Combined with compact high-order MEMS deformable mirrors, fast efficient wavefront control algorithms, high-accuracy calibration, and differential imagers, we believe we can deliver contrast a factor of a hundred or more better than current AO systems and exceed the ExAOC contrast goals with low technological risk. We undertake this conceptual design study with the expectation that we will go on to deliver an ExAOC system within budget on a competitive timescale, and that Gemini, and our team, will become the leaders in extrasolar planetary research. To support this ambitious effort, our partners have committed more than $300,000 in direct cost-sharing, $200,000 of in-kind matching effort, while the CfAO is funding $400,000 of work that is directly applicable to this project.

1 Introduction

This proposal represents our response to the Gemini Announcement of Opportunity No. N231802, to perform a conceptual design study for an Extreme Adaptive Optics Coronagraph (ExAOC). The Gemini Observatory has issued a bold challenge to its astronomical community: make the first direct detection of extra-solar planets. We recognize that an extraordinary level of scientific leadership, technical innovation, and management skills will be necessary to design, build and deploy a ExAOC system capable of imaging Jovian mass planets orbiting stars in the solar neighborhood. We have assembled a outstanding team of scientists and engineers who are committed to the goal of making the first direct detections of planets and answering the Gemini challenge.

Since this is such a complex and different instrument – a combination of an AO system, coronagraph, and integral field unit – this is necessarily a complex proposal. We first outline the key questions in the science case (Section 2) and how these connect to the instrument performance. Any ExAOC system must be driven by a plausible science mission – a system that achieved contrast of 10^9 but only operated on 2^{nd} magnitude stars would be of little interest. We have assembled a world-class science team and developed quantitative tools for modeling planet populations and AO system performance, so that the ExAO design will be optimized for the science requirements. These simulations will be used to refine fundamental parameters of the strawman design and downselect among choices for key subsystems such as the coronagraph and science instrument.

Next, we lay out the strawman instrument design and subsystems (Section 3.) Then we discuss in detail the key questions to be answered during the design study (Section 5). The most important tasks include developing basic system parameters that address the science mission, identifying the technological approaches to key components, and selecting a science instrument based on capability, cost and risk. Section 5 summarizes the project plan (a detailed WBS is presented as in Appendix E.) During this process, our team will be guided by best-practices management (LLNL) and systems engineering (HIA), discussed in Section 6. Three team-wide meetings will be supplemented with videoconferencing and data sharing. Subsystem tasks and interfaces will be clearly defined and tracked. Sections 7 and 8 list the institutions, personnel, and facilities in the project. Appendix A gives a more detailed exploration of the science case, and Appendix B reviews the physics of high-contrast imaging, showing the distinction between a coronagraph and an AO system, and gives the error budget for our strawman system.

Our goal is to construct the world's most advanced system in support of a clear scientific goal – direct detection of a scientifically significant population of planets – and our expert multinational team is the best possible choice to do this.

2 Translating the science mission into instrument requirements

2.1 Extrasolar planets

In the past decade, more than 100 extrasolar planets have been detected through indirect Doppler techniques – a powerful technique but one that is limited by time baseline to semi-major axis < 5 AU. Direct imaging detection of extrasolar planets is potentially an extremely important complement to existing planet detection techniques, and within the reach of a suitable "extreme" adaptive optics (ExAO) system on a 8-m telescope. However, to justify the construction of such a system, several questions must be answered. First, will such an instrument increase our understanding of planetary systems? Second, for reasonable extrapolations of system and planet properties, will the instrument be capable of detecting a significant population of planets? Third, will we be able to determine the properties of the planets themselves? Finally, what additional scientific capabilities can or should such a system have?

Answering these questions in a way that determines the specifications of the instrument will be the goal of our science case development. Appendix A discusses the fundamental scientific questions in more detail. Here we will present the highlights of that discussion and emphasize the ways in which our outstanding science team will guide the instrument design.

2.2 Architecture of Planetary Systems

Doppler surveys show that ~5% of target systems have planets within 3 AU, and a variety of exoplanet systems exist, but they leave long-standing questions unanswered: How do planets form? Is the solar system typical? What is the abundance of solar systems? Doppler surveys also raise a host of new questions such as: What produces the dynamical diversity in exoplanet systems? Direct imaging can answer these questions by offering a fast alternative to Doppler surveys for searching for planets at large stellocentric distances. Characterizing the frequency and orbital geometries of planets beyond 3 AU will finally enable us to answer whether orbital configurations like our own planetary system are commonplace, reveal the zone where planets may form by direct gravitational instability, and uncover traces of planetary migration.

2.3 Direct detection of self-luminous planets

Direct detection of Jovian-mass planets via their reflected sunlight requires a contrast ratio of order $2 \times 10^{-9}(a/5AU)^{-2}$ relative to their parent star. Exo-Jupiters in $a \sim 5$ AU orbits may eventually be detected directly in reflected light by space-based telescopes (Trauger et al. 2003). Because of the inverse square law, reflected light searches, like Doppler searches, are an impractical way to explore the outer (10-30 AU) regions of solar systems. The option we pursue here is to seek the energy radiated by the planet itself, which is independent of *a*. Old planets are cool and dim, but young planets are hot and therefore bright (Figure 2) in the infrared. For example, at 1.6 μm it is possible to detect a 10 Myr-old 3 M_J planet, or a 100 Myr-old 7 M_J planet, orbiting a G2V star at a contrast ratio of only 4 x 10^{-6}. With improved contrast an increasingly large phase space of planets becomes accessible. Better contrast is obviously preferable, but it comes at a penalty. For example, Angel (1994) described an AO system designed to achieve very high contrast ratios using bright guide stars. This system would be suitable for exploring the planetary systems of 13 bright stars (R < 3.8 mag) in the solar neighborhood (< 8 pc). However, the detection of a few planets, although dramatic, would be insufficient scientific impetus given the success of the Doppler searches. It is necessary to show that any proposed instrument can search a scientifically interesting range of semimajor axes and accumulate a statistically significant sample of exoplanets in reasonable observing time.

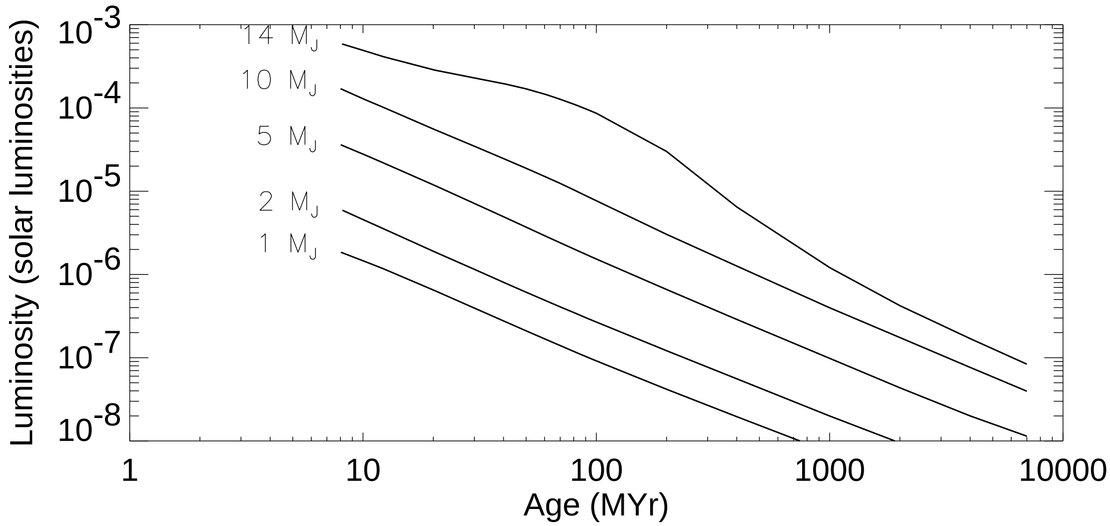
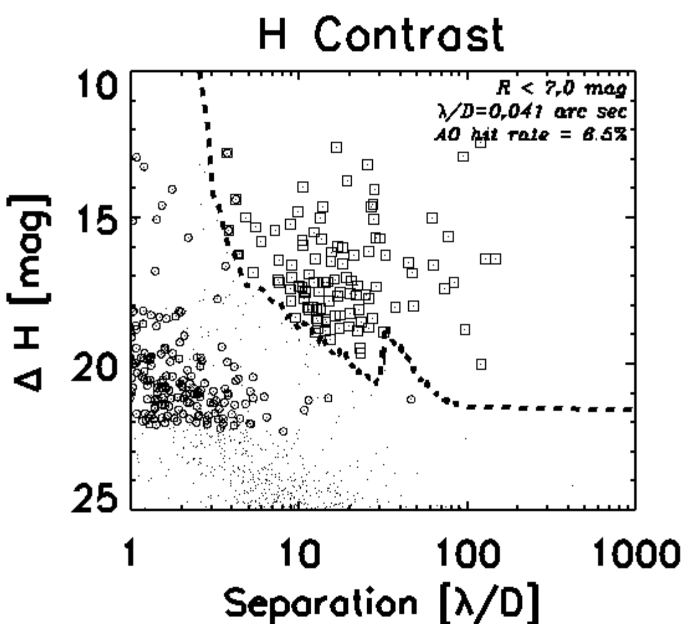


Figure 2: Cooling curves for planetary-mass objects. Jupiter at 4.5 Gyr has $T_{eff} \approx 120$ K. Young massive planets are hot and therefore luminous. The kink in the 14 M_J line is a consequence of deuterium burning and defines the brown dwarf/planet boundary. (Burrows et al. 1997, 2002)

2.4 Methodology for exploring design phase space

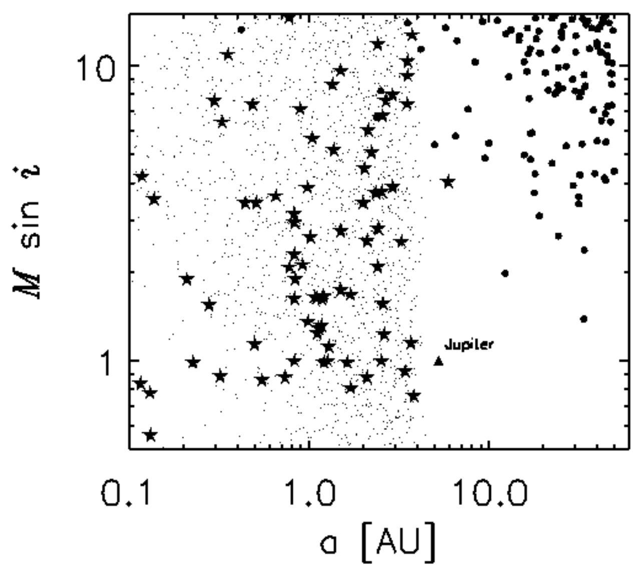
The performance of an exoplanet imager is characterized by contrast ratio at which a companion can be detected. The achievable contrast will be a function of the brightness of the wavefront reference, the angular separation, and observing and wavefront-sensing wavelengths. The detectability of planets in a given sample of target stars can then be estimated by comparing the distribution of relative exoplanet brightness versus angular separation with the expected performance. This comparison also quantifies selection effects that vary with properties of the planet (age, mass, and orbital elements) and of the primary star (spectral type and distance). Our knowledge of the distribution of planetary properties is incomplete, but it is a basic premise that sufficient information exists from Doppler surveys to make a preliminary estimate of this distribution. It is then possible to estimate the scientific impact of different design choices, e.g., precision and accuracy of adaptive optics correction and observing wavelength, and therefore make an informed trade-off between cost and performance.

Figure 3: Detectable companion contrast versus angular separation for our strawman Gemini ExAOC design, showing the direct detection of young luminous planets in a hypothetical survey of field (< 50 pc) stars. The small dots represent the planet population: those detected by ExAOC are drawn with a box, those detectable in current Doppler surveys are shown with a circle. The dashed line shows the contrast threshold (5 σ) for a 1 hour exposure at 1.65 μm. Within 100 λ/D speckle noise dominates. The threshold at large radii is set by detector noise.



The approach we propose involves making a Monte Carlo model for the population of planets in the solar neighborhood. This description includes the mass, age and orbital elements of each accompanying planet. When combined with cooling curves, model atmospheres and the distance to the primary star we can compute the brightness ratio and angular separation at any epoch. We can also compute the reflex motion of the parent star to infer the detectability of the planet by indirect Doppler or astrometric techniques.

Figure 4: Results of the Monte Carlo simulation for a field survey of exoplanets. Heavy filled circles are ExAOC detected planets from the previous figure. Light dots are planets detected by a hypothetical astrometric interferometer (similar to the Keck Outriggers) survey with a duration of 8 years, a magnitude limit of $R < 10$ mag., and a precision of 30 μas. Real exoplanets detected in the Keck/Lick Doppler survey are shown as stars (Marcy 2004). This example illustrates how ExAOC explores a complementary phase space to indirect searches.



A preliminary version of the Monte Carlo analysis has been performed for our strawman ExAOC design. This shows that we can detect ~ 6% of the planets in a survey of field stars. The results are shown in Figure 3. In this example 1703 stars (R < 7 mag.), representing a northern hemisphere survey, are observed and 110 planets are detected.

This calculation reveals the selection biases that affect a direct imaging survey and illustrates how such a survey populates planet-discovery phase space. Figure 4 compares the catalog of planets detected by Doppler surveys, a hypothetical astrometric survey and by ExAOC. This comparison shows that ExAOC does probe the outer regions of solar systems and can answer the key science questions related to planet formation and migration.

During the conceptual design study phase we will improve the fidelity of this simulation and broaden its applicability. Specific tasks include capturing the performance of the science instrument, including suppression of speckle noise by multiwavlength imaging, and assembly of catalogs of field stars, associations and clusters with estimates of distance and age. We will perform a full exploration of the AO, coronagraph, and science instrument design phase space: wavefront sensor subaperture size, coronagraph inner working distances, field of view, observing and sensing wavelengths, and science camera configurations.

A particularly interesting complement to broad field-star surveys are targeted surveys of young clusters and associations, where the ExAOC detection rate can approach 50%. We will evaluate the suitable targets for such a survey, which will bear strongly on the question of which hemisphere ExAOC should be located in.

2.5 Study of circumstellar debris disks

The second key scientific area for ExAOC will be the study of the circumstellar dust disks surrounding nearby stars. Such disks are the extrasolar analogs of our Zodiacal dust disk (3 AU) and the dust complex generated in the Kuiper Belt (40-50 AU; Ladgraf et al. 2002). These are optically thin structures of dust created by the collisional erosion of larger solid bodies. Such disks are scientifically interesting as tracers of planetary systems' structure and formation. By contrast to planetary systems, several such disks have been imaged in the near-infrared, and their presence around a star can often be inferred from far-infrared observations, making them a guaranteed successes for an ExAOC system whose sensitivity significantly exceeds that of existing facilities. However, detection of these diffuse disks is challenging and places different requirements on ExAOC, requiring sensitivity to low surface brightness extended emission, excellent PSF subtraction, and polarimetric capabilities.

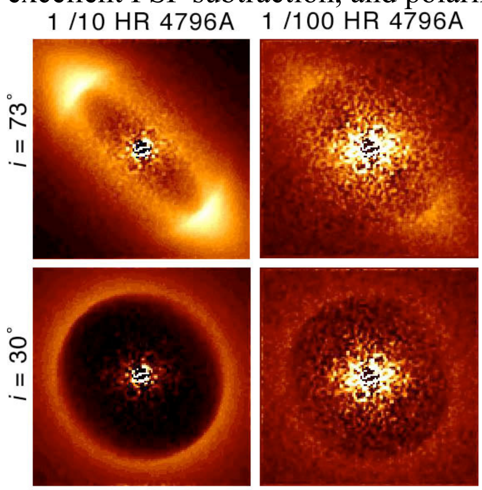


Figure 5 : Simulations of debris disk observations by ExAOC representing a 10 second integration. The distance from the star to the edge of the dust ring is 1". The disk model is based on observations of HR 4796A. The model disks are presented at different inclinations to the line of sight and at two optical depths: HR4796A/10 (left) and HR4796A/100 (right). The disk signal is extracted by performing a PSF subtraction with ~20% seeing fluctuations between the reference and science image.

2.6 Secondary scientific roles

The extremely high Strehl ratio, even at short wavelengths, of an ExAOC system will open up a series of secondary scientific roles, including imaging of bright solar-system targets, studies of outflows from evolved stars, and possibly studies of crowded fields near a bright reference star. Although such missions should not drive the design, neither should we inadvertently make design decisions that close off these avenues without an awareness of the benefits and costs; we will therefore explore some representative cases such as planetary science observations.

2.7 Requirements and science case interactions with design

Our preliminary science requirements are embodied in the ExAOC straw man design described in section 3. A primary task of the science team during the conceptual design phase is to review this list for completeness and to conduct trade studies to optimize our choices. For some parameters, e.g. system throughput, the trade is performance vs. cost, and the goal of the science team is to provide a scoring scheme so that practical choices can be made. However, some trades are more fundamental, in the sense that genuine optimal configurations exist given limits imposed by the atmosphere and the diameter of the telescope primary mirrors. A good example is the choice of subaperture size in the wavefront sensor. A smaller subaperture size means higher order correction. Higher order correction translates into higher contrast, but at the cost of a brighter limiting magnitude for the target star and a reduction of number of accessible target stars.

The following table itemizes the science topics and their relation to instrument requirements. We have called out one or more aspects of each topic that we expect to place the most stringent constraints on each requirement.

Table 1: Interactions between science case and instrument requirements.

	Exoplanet field survey	Cluster exoplanet survey	Exoplanet properties	Debris & protostellar disks	Solar system
Contrast vs. angular separation	Planet detection rate				
Wavelength range	Sensitivity to young planets			Constrain grain size distribution	Short λ for max. angular resolution
Spectral resolution	Multi-color speckle rejection		Teff/log(g) diagnostics		Ice mineralogy
Polarimetry	Distinguish exoplanets & zodiacal blobs			Sensitivity to dust scattering	Atmospheric hazes
Throughput & sensitivity			Planet spectroscopy		
WFS mag. limit & wavelength		Lock AO on late type stars		Lock AO on T Tauri stars	Lock AO on extended objects
Operability [1]	Time to complete survey			Accumulate deep exposures	
Zenith distance limit	Efficient survey strategy				
Accessible Dec. range		Young assoc. vs. nearby clusters			
Astrometric accuracy & precision	Common proper motion		Orbital eccentricity		
Flat fielding accuracy	Dynamic range			Sensitivity to surface brightness	
Photometric accuracy & precision			Magnitudes & colors		
Field of view		Inner working distance		Outer extent of debris disks	

[1] "Operability" denotes both system reliability and robustness against varying atmospheric conditions.

3 System architecture: Introduction

The ExAO system design can be conceptually be broken down into three components: an **adaptive optics system**, producing the best possible wavefront; a **coronagraph**, suppressing diffraction; and a **science instrument**, imaging the resulting high-contrast PSF while (if possible) removing as much as possible of the remaining wavefront errors. Interconnected with all three is a **calibration system** that adjusts the AO system's control point such that the wavefront is "best possible" not at the wavefront sensor, but in the correct plane in the science path.

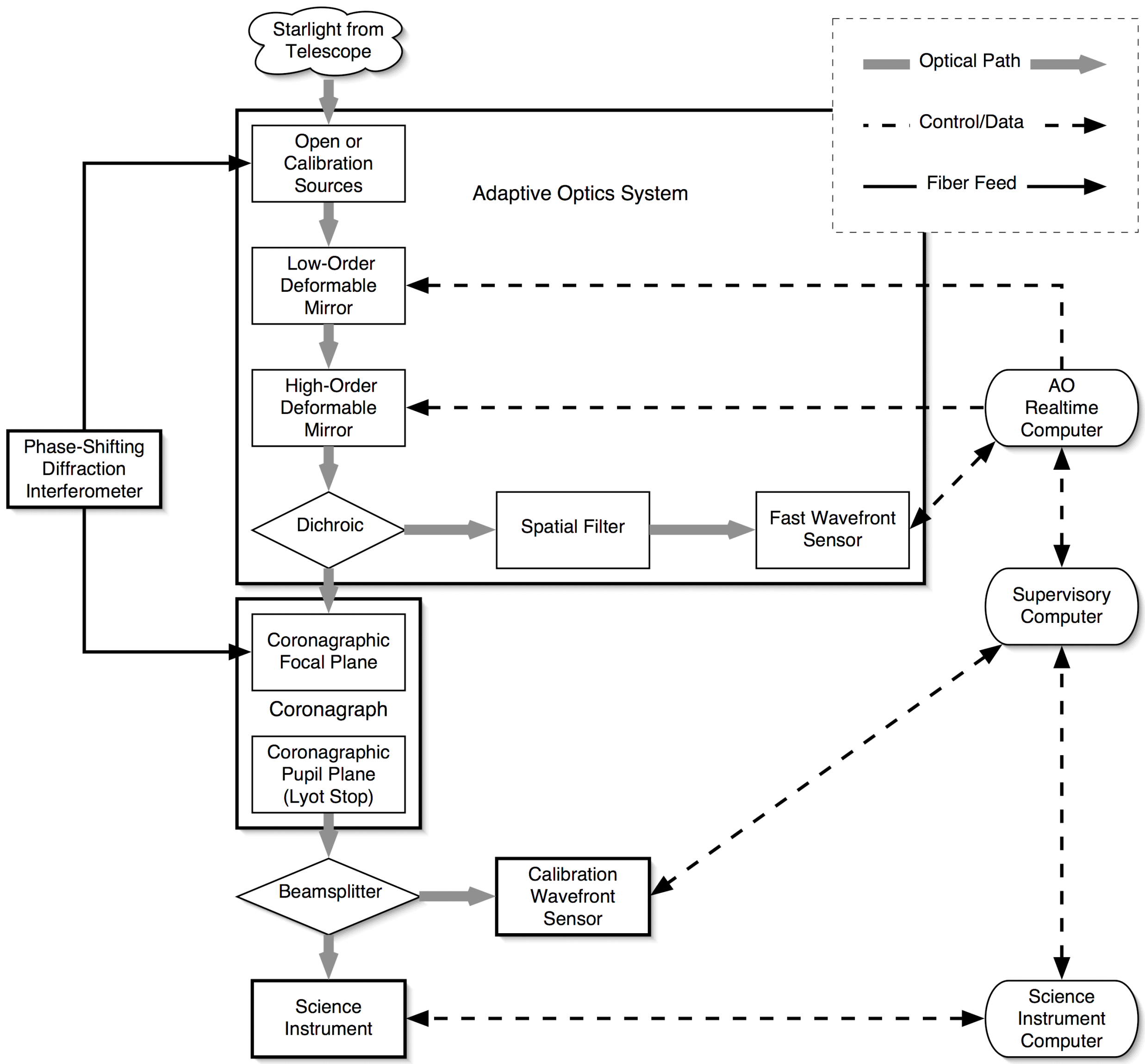


Figure 6: Block diagram of ExAOC system

Figure 6 shows a block diagram of the ExAOC system, organized along these principles. The architecture of each subsystem is discussed in the following sections. This modular approach represents the conceptually simplest architecture as a starting point, not necessarily the ultimate design. Once strawman designs exist for each subsystem we will examine whether increased integration can improve performance, decrease system mass, or decrease risk by reducing the number of optical surfaces. For example, rather than a standalone warm coronagraph, a Lyot coronagraph could be incorporated into the science instrument dewar; since the IR science instrument requires a reimaged pupil this would reduce the number of optical surfaces, at the cost of requiring the highly accurate coronagraph mechanisms to be cryogenic. Overall, the architecture described below can be thought of as a baseline against which to compare performance tradeoff studies and system optimizations; as these identify performance bottlenecks and risk areas, we will explore different versions of this design before moving to detailed design.

Appendix B discusses the underlying methodology used to predict high-contrast performance and presents strawman error budgets for the ExAO system.

Table 2: Comparison of ExAOC and Altair parameters

Parameter	**Altair**	**ExAOC**
Subaperture size	0.66 m	0.13 – 0.26 m
Number of subapertures across pupil	12x12	62x62 – 31x31
Update rate	1000 Hz	2500 Hz
Number of actuators on DM	177	4096
DM size	10 cm	~3 mm
Internal static wavefront error before / after calibration	200 nm / 50 nm	45-24 nm / 15-11 nm
WFS CCD size	80x80	128x128

3.1 AO system architecture

Figure 7 shows an optical layout of the AO subsystem and coronagraph. The architecture represents a careful balance between "classic" AO architecture (e.g. visible-light Shack-Hartmann wavefront sensing) with technologically feasible innovations (the spatially-filtered wavefront sensor, MEMS deformable mirrors, and precision metrology and calibration) to achieve the ExAOC goals on the Gemini timetable; essentially all technology to be used exists, has been prototyped, or represents a modest evolution on current devices.

3.1.1 Optical design:

The AO relay consists of all the ExAOC optics from the Cassegrain port to just before the coronagraph. Since ExAOC will have two deformable mirrors, the strawman design will have two pupils conjugate to the telescope primary, each with a pair of OAPs associated with it. This point will be revisited in the conceptual design phase: the small FOV may allow at least one of the DM's to be in a position other than a pupil plane. We will explore more sophisticated designs with fewer surfaces, including designs that produce an output pupil before or after the output focus with no additional optics.

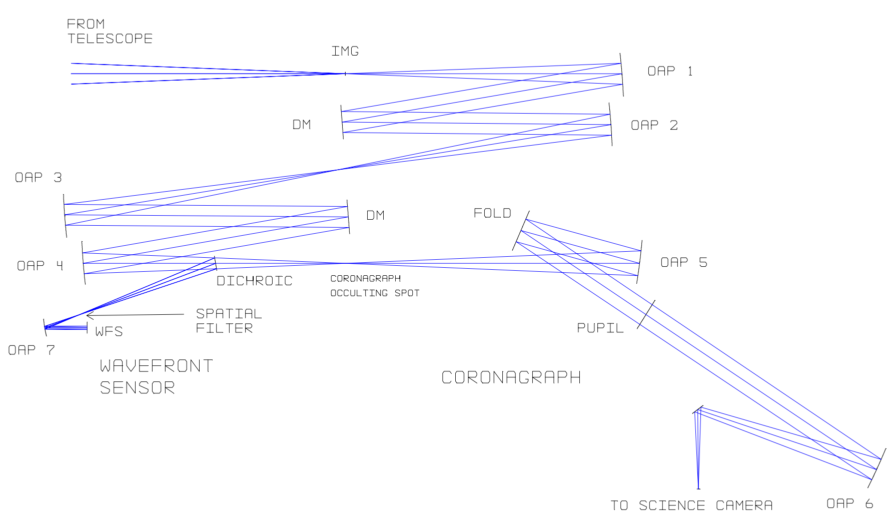


Figure 7: Basic optical layout of AO system and coronagraph, showing the AO relay off-axis parabolas (OAP)s, the two deformable mirrors (DM), the dichroic feeding the spatially-filtered WFS, and the coronagraph. Not shown are steering and fast tip/tilt mirrors or the calibration wavefront sensor.

3.1.2 Deformable mirrors

ExAO performance models indicate that we require 2000-4000 actuators to reach contrasts of 10^7 over a large range of radii. Classical deformable mirrors cost $1000/actuator and have a size of ~1 cm^2/actutator –prohibitive for this application. We will study two primary technological alternatives, with the preferred option being silicon Micro Electro Mechanical Systems (MEMS) deformable mirrors. Section 5.2.2 discusses the technology development path to 4096 (64x64) actuator mirrors and possible technological alternatives.

One significant limitation of high-density DM devices, however, is their stroke (<2 microns.) Hence ExAO will require two deformable mirrors in a "woofer-tweeter" configuration, the "woofer" DM being relatively low order (but high stroke). Rather than introduce additional optics, we intend to control both deformable mirrors with a single wavefront sensor.

3.1.3 Spatially Filtered Wavefront Sensor (SFWFS)

As its primary or fast wavefront sensor our strawman uses a Shack-Hartmann (S-H) type with a novel spatial filter. S-H sensors are well-understood, forming the basis of most adaptive optics systems. They are optically simple to implement, operate at visible-light or near-IR wavelengths (given the appropriate detector), have relatively large dynamic range, operate at almost any Strehl ratio, and are easily scaled to high orders. Alternative architectures such as point-diffraction interferometric wavefront sensors (Angel 1994) or focal-plane wavefront sensors (Angel 2004 in press) have yet to be demonstrated in a closed-loop AO system; we have opted in this area to use proven technology, though we will explore the behavior and feasibility of other sensors during the preliminary error budget phase.

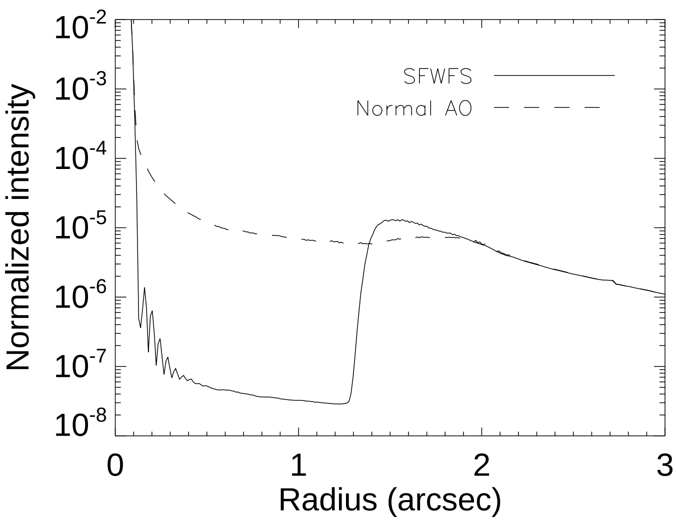


Figure 8: Radially-averaged intensity profiles from a detailed closed-loop simulation of an AO system without ("Normal AO") and with ("SFWFS") the aliasing suppression provided by the spatially-filtered wavefront sensor. Diffraction has been suppressed by pupil apodization. Intensity is normalized so that the peak of the apodized PSF=1.0. This simulation has subaperture size d=13 cm and r_0=20 cm at 500 nm. This simulation has no WFS measurement noise or temporal bandwidth errors, which act to partially fill in the dark hole.

The most innovative feature of the main wavefront sensor is the use of a spatial filter to suppress aliasing effects. In the general case, AO systems operate using sampled measurements of the derivative of the phase every subaperture width d in the pupil plane. If the phase is not bandlimited (i.e. has both high and low spatial frequency components), aliasing will occur. This aliasing will bring errors from high to low spatial frequencies and hence scatter light into the AO control radius $\theta_{AO}=\lambda/d$. Since high spatial frequencies correspond to large angles, this can be prevented by implementing a spatial filter – a square hole or adjustable iris of size λ/d - as a field stop of width θ_{AO} in the wavefront sensor focal plane (see Figure 7). Detailed Fourier-optics simulations (Figure 8 and Poyneer and Macintosh 2004) show that this acts as a non-ideal low-pass filter on the phase. With aliasing removed, the AO system can almost perfectly reproduce the input aberrations and mid spatial frequencies, resulting in a PSF with a characteristic "dark hole". It is capable of up to 5 orders of magnitude suppression on high spatial frequency power and can reduce the intensity of the PSF inside a square "dark hole" by up to two orders of magnitude. The SFWFS allows a conventional Shack-Hartmann sensor to achieve performance comparable to the focal-plane wavefront sensor (Angel 2004) with existing technology.

3.2 Coronagraph architecture

With the wavefront under precise control, the PSF inside the AO control radius is dominated by the light in the diffraction pattern of the telescope. A stable PSF can be simply subtracted, but with a noise penalty from the photon and speckle noise. A coronagraph can effectively suppress the diffracted light and the first order, "pinned", speckle thus rejecting these as noise sources. Amongst the zoo of coronagraphs, all operate fundamentally by tapering or modifying the spatial frequency content of the light in one (e.g. apodized pupil) or more (e.g. Lyot coronagraph) steps. Lyot type coronagraphs are generally favored since the combination of two stages rejects the light before it reaches the focal plane. The baseline coronagraph architecture therefore includes an optical relay with an image and pupil plane at which stops are placed. Recent progress in coronagraphs has yielded a number of possible improvements in the design of these stops that will be considered in this design study. Coronagraphy is the most mature field of the ExAOC subsystems.

3.3 Science instrument

As discussed in section 5.7, simultaneous imaging at multiple wavelengths can attenuate speckle noise if the differential aberrations between the wavelengths are minimized. Tiger-type IFU like OSIRIS (Larkin et al. 2003) and the IFU-based MWI device Multi-Color Detector Assembly (MCDA; Doyon et al. 2004, Marois et al. 2004), both intrinsically immune to differential aberrations, constitute our two strawman science camera concepts. We shall study these during the design phase, with initial analysis of the fundamental and technological limitations to these approaches followed by a downselect to a single instrument design (or a hybrid of the two.) Section 5.7 discusses some of the tradeoffs between these approaches. The science instrument will also include a differential simultaneous polarimetric mode (Potter et al. 2002, Perrin et al 2004).

3.4 Overall computer architecture

The computer system being proposed for the ExAOC instrument, to be refined during the Conceptual Design, consists of three subsystems: the Supervisory / Components Controller Computer (SCC), the Adaptive Optics Computer (AOC), and the Science Instrument Computer (SIC). Normally, the SCC will serve as the interface between the ExAOC instrument and the outside world. A study will be performed to determine whether Gemini's new instrument API or the current EPICS interface as used by Altair will be used for the ExAOC implementation, based on Gemini preference, software re-use, risk, cost, and development time. Besides being the communications 'hub' of the instrument, the SCC will serve as the instrument sequencer, provide component control, manage the data pipeline, perform some data processing tasks, and perform calibration and alignment tasks.

The AOC and SIC subsystems will communicate with the SCC through a dedicated interface (dedicated Ethernet or reflective memory). The AOC (see section 5.3) will perform all real-time aspects of adaptive optics control, provide data and status to the SCC as necessary, perform some data processing tasks, and perform some calibration and alignment tasks.

The SIC will perform all science-instrument related data gathering tasks, provide data and status to the SCC as necessary, perform some data processing tasks, and perform some calibration tasks. The current plan is that all three subsystems will be Linux-based, with at least the AOC running a real-time variant. Other OS/RTOS alternatives will also be explored. All three subsystems will use commercial hardware wherever possible. It is important to note that members of our team have already developed similar systems that do virtually everything described in this subsection, allowing our team to take advantage of its experience and to reuse hardware and software where appropriate.

3.5 Calibration and metrology system

As discussed in section 11.3, one of the most challenging aspects of the system design is the overall static wavefront error quality, which must be in the 1-10 nm range at mid spatial frequencies. This represents an order of magnitude improvement over the best current ground-based AO systems. We believe that this is feasible; it is comparable to the wavefront error requirements for EUV lithography, in which LLNL played a major role, and an order of magnitude more relaxed than the requirements for space-based coronagraphs such as TPF or Eclipse being developed at JPL (Trauger et al 2003). We will achieve this in three ways. First, use of modified phase retrieval or speckle cleaning algorithms to calibrate the system using its internal reference source. Second, we will incorporate a LLNL-developed interferometer to provide sub-nm metrology of the system during calibration and in-between observations (Section 5.5.3). Third, we will study concepts for a precision "calibration wavefront sensor" (CWS), a low temporal-bandwidth/high-accuracy wavefront sensor operating at or near the science wavelength and science camera location to measure the time-averaged wavefront and correct the fast wavefront sensor control point during integrations. Section 5.3 discusses alternatives for this CWS.

4 Project plan

The ExAOC design study will move, broadly, through two phases. The first is an initial definition phase: selecting the basic parameters for the system – subaperture size, AO update rate, coronagraph inner working distance – through simulations and interaction with the science requirements. During this phase, we will also explore multiple concepts for the coronagraph, science instrument, and calibration subsystems, and verify the technical readiness of other key components. At the conclusion of this phase we will have system and subsystem performance requirements encompassed in the FPRD and error budgets. The second phase is a design phase, during which the subsystems and the integrated system designs are advanced to the CoDR level, with basic optomechanical or software designs (supplemented by detailed analysis of key subsystems, such as the wavefront sensor), and verification that the desired error budget is practical.

Different subsystems will move through this process at different rates. During the past 1.5 years, the CfAO has been working on a strawman ExAO system design, with the result that some components – such as the realtime AOC – are nearly ready for the design phase. Other systems, such as the calibration subsystem, are less well defined and will spend most of the design study period in the definition phase. Nonetheless, the goal is to have most of these systems defined by the mid-term review.

Appendix E shows a detailed work breakdown structure for the project assuming a May 3 start date. The key tasks to be undertaken by our team are summarized below. For each task, we list the funding source(s). G indicates direct Gemini funding and direct matching funds. LAO indicates tasks co-funded by the Laboratory for Adaptive Optics at UCSC. IK indicates tasks carried out as in-kind cofunding (e.g. tasks carried out by university faculty.) CfAO indicates related subprojects that are directly funded by the Center for Adaptive Optics. Section 9 discusses the breakdown of the budget among different funding sources in more detail.

May-June 2004

- Establish the predicted sensitivity of a range of possible design combinations using analytic error budgets and some simulations (CfAO)
- Develop the tools for simulating and evaluating the scientific capabilities of a given system (IK)
- Review existing Gemini designs for possible reuse (G)
- Design overall computer architecture and interfaces to Gemini (G/LAO)
- Evaluate candidate components for WFS and DM (CfAO)
- Design AO and WFS optical system (CfAO)
- Investigate key questions in AO control algorithms (G at HIA, CfAO at LLNL)
- Identify four basic coronagraph designs, and carry out simulation and evaluation of manufacturability (CfAO)
- Define of calibration subsystem requirements and identification of candidate techniques (CfAO)
- Define parameters and capabilities of IFU and MCDA (G, IK)
- Define basic mechanical layout (LAO)
- Project leadership and management (LAO, G)

July-September 2004:

- Evaluate proposed designs against core science requirements (IK)
- Select final strawman system design parameters (CfAO)
- Generate complete error budget and simulations of strawman design (CfAO)
- Generate final error/performance budgets for subsystems (LAO, G)
- Define interfaces between computer subsystems (LAO, G)
- Design components controller and user interface subsystems (LAO)
- Summarize tolerances and alignment procedure for AO/WFS optics (LAO)
- Mechanical design of AO system (LAO)
- Identify AOC requirements (CfAO)
- Downselect coronagraph to two designs and begin detailed design and simulation (CfAO)
- Simulate and model calibration WFS techniques (CfAO)
- Basic IFU optical design (G, IK)
- Evaluate feasibility of key components of MCDA (G)
- Compare IFU and MCDA performance and risks and downselect one science instrument (G)
- Draft initial OCDD (LAO)
- Draft initial FPRD (G)
- Project leadership and management (LAO, G)

October-December 2004:

- Submit draft OCDD and FPRD (LAO, G)
- Develop science case for adjunct science modes and evaluate against strawman design (IK)
- WFS mechanical design (LAO)
- Develop preliminary WBS and budget for ExAOC (LAO)
- Develop improved simulation tools for use in PDR phase (LAO)
- Develop AOC software design (CfAO)
- Identify AOC hardware design (CfAO)

- Predict sensitivity of coronagraphs including realistic component properties (CfAO)
- Evaluate and rank calibration techniques and downselect (CfAO)
- Detailed design and costing of selected science instrument (G)
- Complete optics bench and enclosure design for instrument (LAO)
- Submit initial OCDD and FPRD (LAO/G)
- Final WBS and costing for all subsystems (LAO/G)
- Revise OCDD and FPRD (LAO/G)
- Write conceptual design study report (LAO)
- Submit conceptual design study documentation (LAO)

Although the beginning-points for various components of the Conceptual Design Study will vary depending on prior work, the middle and end-points will be the same: meeting the milestones and producing the deliverables. To coordinate deliverable production and to guarantee delivery on schedule, specific individuals will be ultimately responsible for each deliverable as follows:

OCDD	Macintosh
FPRD	Murowinski
Design Study Documentation Outline	Palmer
Preliminary WBS, schedule, budget	Palmer
Design Study Documentation	Macintosh

Tasks are keyed to milestones as necessary. For example, science case work for the principal science driver (WBS 1.3.1) will be completed in time to feed into the draft initial OCDD.

Another important date in the Conceptual Design is the mid-term review (WBS 1.2.3). It is at that time that a decision will be made as to which science instrument will be carried forward for the remainder of the project. This means that the feasibility of both instrument (IFU and multi-wavelength imager) will be studied for the first half of the project and then a conceptual design will be produced for one of the two.

Project Milestones	
Commence work	5/3/04
Down-select science instrument	9/1/04
Deliver draft of Initial OCDD	9/20/04
Deliver draft of Initial FPRD	9/20/04
Submit Design Study Documentation Outline	10/11/04
Deliver preliminary WBS, schedule, and budget	11/15/04
Deliver Initial OCDD	11/29/04
Deliver Initial FPRD	11/29/04
Deliver Design Study Documentation, including revised IOCDD and IFPRD	12/30/04
Conceptual Design Study Review (CoDR)	TBD by Gemini
Completion of all work	CoDR + 1 month

5 Key issues for design study

In the following sections we identify the major technical areas to be explored in the design study. The goal is to identify a set of fundamental system design parameters that meet our scientific goals, and establish the technical feasibility and approach to implementing this design. The most crucial areas are:

- identifying the key components – particularly the WFS, DM, and AO controller
- identifying a wavefront calibration and metrology approach that can reach our stringent static wavefront error goals
- selecting between a multi-channel imager science instrument and an integral field unit based on performance, cost, and technical risk
- evaluating the magnitude of flexure effects that will contribute to final wavefront error
- producing a final integrated error budget and performance simulations for the system

Names in italics in each subsection below indicate who has lead responsibility for each area.

5.1 Fundamental system design parameters and error budget

(Macintosh, LLNL)

The first set of questions to be addressed during the design study define the instruments fundamental performance. Most fundamental is the tradeoff between subaperture size, contrast, technological feasibility, and limiting magnitude. The baseline system with 62 subapertures across the Gemini primary will achieve extremely high contrast, but performance will start to degrade for m_I>5 stars. Fewer subapertures translates into lower contrast and a smaller "dark hole", but broader target reach. We will use analytic models (Section 11.3) to predict performance for a family of system designs, and the science methodology discussed in section 2.4 to evaluate these with respect to the core science goals. One attractive option to achieve high contrast on the brightest stars and moderate contrast on a larger sample is a selectable lenslet array, changing between 62x62 and 31x31 subapertures on the wavefront sensor with slaved 2x2 groups of DM actuators.

During this process we will develop more refined error budgets (Section 11.3), incorporating the likely internal optical errors and modeling additional sources of external error such as the Gemini M1 and M2 mirrors, atmospheric scintillation, and chromatic errors. The error budget will be used to apportion optical tolerances among subsystems as the design is refined, and to identify fundamental limits to sensitivity.

5.2 AO component selection and design

5.2.1 Fast wavefront sensor detector (Palmer, LLNL)

The minimum requirements for the fast wavefront sensor are at the state of the art of fast CCD technology: ~60x60 subapertures running at ~2500 Hz with ~10 electrons noise. The leading candidate for the CCD for the ExAOC WFS is the MIT / Lincoln Labs (MIT/LL) 128x128 device. This device has a proven track record, in use at the USAF AO systems at AEOS and Starfire optical range. LLNL has experience procuring MIT/LL devices. The device is capable of running at ~4000 frames per second with roughly 12 to 15 electrons of noise, and MIT/LL indicates that 2500 frames per second, with ~10 electrons of noise is a reasonable goal. A possible alternative to the MIT/LL device is the E2V CCD50; however, this device has not (to our knowledge) been deployed in an operational AO system, and currently appears limited to

~kHz frame rates. An issue for either CCD is charge diffusion blurring the WFS spots; the effects of this and the requirements for CCD plate scale will be examined in the design study.

128x128 pixels for our baseline 62x62 system gives 2x2 pixels per subaperture with no guard bands. The lack of guard bands could complicate system alignment and constrains the CCD plate scale; the use of quad cells introduces a slight sensitivity to atmospheric seeing and WFS spot size. A 180x180 or 256x256 pixel CCD would mitigate these. MIT/LL has estimates that developing such a detector is a $1M project. We will use detailed simulations to establish the benefits of such a device and we will explore establishing a collaboration with other groups (the CARA group funded by the NSF AODP and the ESO planet-finder groups) to co-fund such development. However, we believe that ExAOC can reach its performance goals with the existing MIT/LL chip.

Infrared wavefront sensors are attractive for ExAO, in that they minimize chromatic errors, and may provide enhanced sensitivity to very red target stars. IR array technology is currently inadequate for our needs, but our UCLA co-Is are involved in development of next-generation IR WFS detectors and will evaluate their suitability and technology readiness.

5.2.2 Deformable mirror (Olivier, LLNL; Bierden and Bifano, Boston Micromachines)

The deformable mirror is the only key item of technology for our ExAO strawman that is not currently available. We desire a 64x64 actuator DM. The largest macroscopic glass deformable mirrors are ~1000 actuators.

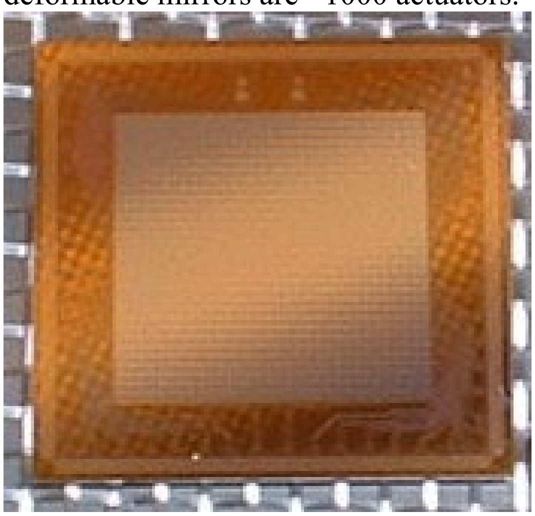


Figure 9: Boston micromachines 1024-actuator DM (uncoated). The active area is ~1 cm^2

By far the most promising technology for our needs is silicon Micro-Electro-Mechanical-Systems (MEMS) deformable mirrors. Manufactured with micromachining technology, MEMS are compact and scale to large actuator counts. Continuous-surface MEMS deformable mirrors are currently available from Boston Micromachines (BM) with 1024 actuators. A continuous gold-coated polysilicon membrane is bonded to MEMS actuators. LLNL has tested a segmented version of these devices in a horizontal-path adaptive optics system (Baker et al. 2004a, 2004b) with impressive results; the mirror repeatability is good enough that the system achieved an *open-loop* Strehl ratio of ~0.5 at 1.6 microns over a 1 km horizontal path. The technical risks with MEMS are the actuator reliability and flatness of the current devices, and the feasibility of scaling to 4096 actuators. We will use co-funding to address both risk areas during the proposal. The UCSC Laboratory for Adaptive Optics (LAO) has already signed a contract with BM to take delivery of a series of 1024-actuator continuous DMs for testing in the ExAO testbed (section 5.12.) The goal of this series will be to reach a device with no dead actuators in the illuminated area, characterize the high-contrast PSF obtained with the device, and measure the stability of the correction.

Second, as part of this project we will fund a detailed design at Boston Micromachines of a 4096-actuator MEMS. The result of this design study will be a readiness estimate and cost for a proposed 4096-actuator MEMS device.

As a risk-reduction strategy we will also study other phase correctors. LLNL has a major role in the CfAO MEMS development effort as well as DARPA MEMS AO efforts, and we remain aware of the state of the art in the field; currently no device is even remotely comparable to the BM mirror in technological readiness, but we will inventory manufacturers for this study. In the non-MEMS area, our JPL group has considerable experience with the Xinetics monolithic mirrors. These have been demonstrated in 32x32 sizes, with 48x48 devices planned as well as modular devices made by combining 4 32x32. Xinetics has developed bonding and polishing strategies resulting in a DM with very good surface quality and near-perfect actuator yield. In the JPL HCIT they have demonstrated controllability down to 0.025 nm and excellent actuator yield. However, these devices are not commercially available and their price may be significantly higher than MEMS.

5.2.3 Wavefront sensor optical design and components (Bauman, LLNL)

By far the largest source of non-common-path aberrations is likely to be the wavefront sensor itself (since the aberrations are measured relative to the coronagraph input, the science camera does not contribute.) There are three topics to assess for the WFS leg: the collimating optic, the lenslet array, and the relay (if any) between the lenslet array and the CCD. The conceptual design study will assess the trade-offs between chromatic aberrations, field aberrations, manufacturability, and cost. The lenslet array will have demanding requirements for the regularity of the optical axes of the lenslets, since irregularity in the lenslets translate directly to non-common path error. We have identified a vendor promising sub-micron lenslet regularity and will be evaluating lenslet array samples in the LAO testbed. With respect to the relay between the lenslet array and the CCD, odd aberrations (e.g., coma and distortion) which move the centroids away from the chief ray directly translate to non-common path error, while even aberrations (e.g., focus, astigmatism), couple into non-common path error indirectly via spot size changes.

The number of non-common path optics can be reduced to a minimum by designing the AO relay to have a real pupil located downstream of the final image plane without any intervening optics. This would provide an image plane for the WFS spatial filter as well as a pupil plane for the WFS lenslets. The only non-common optics, then, are the dichroic and lenslets themselves.

5.2.4 Dichroic (Bauman, LLNL)

Another significant potential source of non-common-path aberrations will be the dichroic beamsplitter(s); one beam sees errors in the surface in reflection, the other only in transmission. (In addition, since the dichroic is likely in a converging beam, even a perfect dichroic induces astigmatism.) The coatings group at LLNL has successfully deposited complex EUV multilayer coatings on EUV lithography optics with sub-nm surface quality; this technology could potentially be adapted for dichroic manufacture, albeit at high cost. Pellicle-type beamsplitters are also attractive, as they introduce no fundamental wavefront errors. We will explore dichroic wavefront quality with commercial manufacturers and the LLNL optics groups, select an appropriate technology, and incorporate these into the system error budget.

5.3 Real-time control architecture

(Palmer, LLNL)

The traditional vector-matrix-multiply method (VMM) for wavefront reconstruction scales as $O(N^2)$, where N is the number of DM actuators. For ExAOC, VMM is unfeasible on off-the-shelf hardware. Instead, based on a inventory of the maturity of existing computationally efficient reconstructors, we are planning to use Fourier Transform Reconstruction (FTR) (Poyneer, Gavel, & Brase 2002), which has been developed at LLNL and experimentally verified at Palomar (Poyneer, Troy, Macintosh, & Gavel 2003). Key issues in the development of AO control algorithms are discussed in section 4.4. Preliminary analysis indicates that the FTR will require 1.1 GFLOPS (10^9 floating point operations per second) for a 2.5 kHz frame rate on a 64 by 64 system. It has been determined that a quad-Pentium server will meet the processing needs of the AOC. If further development leads to more processing power requirements, additional power (such as a DSP board) can be added into the server.

I/O will be a greater challenge. Again, commercial hardware and software will be used where possible. Although other RTOSes will be explored, the current plan is that the AOC will be based on a real-time variant of Linux (e.g., FSMLabs' RTLinux) to permit efficient interrupt handling and to facilitate the use of off-the-shelf software drivers where possible. Candidate DMA and frame grabber boards have been identified. It is planned that existing VME-based DAC boards will be used with a very-high-speed bus bridge, to drive the DM. Overall data flow and hardware choices will be verified during the conceptual design. The current plan is that the AOC software architecture will be based on the recent Lick control system implementation (which is Pentium/PCI/RTLinux based) with several refinements to control algorithms and system optimization based on the Altair architecture.

5.4 AO control algorithms development

(Veran, HIA; Poyneer, LLNL)

The FTR will be carefully evaluated and optimized. During the Conceptual Design phase, we will study how noise propagates through the standard FTR reconstruction filter and develop optimal filters, directly in Fourier mode space, to maximize the contrast in the output image. We will compare the performance of the optimal Fourier filters with the more traditional optimal modal control approach (Gendron and Léna 1994.) Of particular interest will be to identify invisible modes such as global and local and verify that they are well rejected by the Fourier filtering. We will also study how optimal filters can be adapted to changing observing conditions and estimate how much computing power / data throughput will be required for the optimization process.

We will also study wavefront prediction algorithms to reduce the temporal error, a big contributor to the overall error budget. Our approach will be to favor prediction schemes that do not rely on a priori assumptions such as Taylor frozen flow and focus on the prediction of low order modes using adaptive processes (see e.g. Dessenne 1998).

The WFS will operate in a quad-cell configuration. This leaves the system susceptible to variations in spot size and hence WFS gain, which leads to increased error on the science camera due to non-common-path aberrations. However, simulations show that the anti-aliasing spatial filter in the WFS path produces spots whose size is only weakly dependent on r_0. During the Conceptual Design phase, we will characterize the expected fluctuation in spot size and assess whether spot size tracking techniques such as dithering are required.

Even with the best wavefront estimation, high accuracy wavefront correction will not be achievable unless the DM device can be controlled to very small tolerances of error. Tests at LAO of a 32 x 32 MEMS will characterize intrinsic effects such as non-linear voltage-to-displacement actuator responses, variation of response from actuator to actuator and `cross-talk' between neighboring actuators. Control strategies that exploit these characteristics need to be developed. We will also address DM control related issues that might limit performance, such as "dead" actuator, "clipping" of actuator commands and control of un-illuminated actuators. Finally, we will study how to best split the correction between the high order and the low order DMs.

5.5 Study of calibration alternatives

(Wallace, JPL)

A high-contrast observation for extrasolar planet detection requires a fundamental shift in thinking. Canonical AO systems introduce significant amounts of non-commonality between the WFS and the science camera. Aside from the typical non-common-path optics that introduce a WFS bias, differences in the optical passband and field points used for sensing errors versus collecting science imagery yield temporal and chromatic biases. The biases result in residual uncorrected wavefront errors that are unacceptable for high contrast imaging.

In order to combat the effects of this non-commonality, we will employ a fundamental shift in AO architecture. We propose a tight integration between: 1) the coronagraph, 2) a device we call the calibration wavefront sensor (CWFS) and 3) the science camera. The calibration WFS will share the same optical band, and the collocation of all these instruments minimizes the spatial non-commonality.

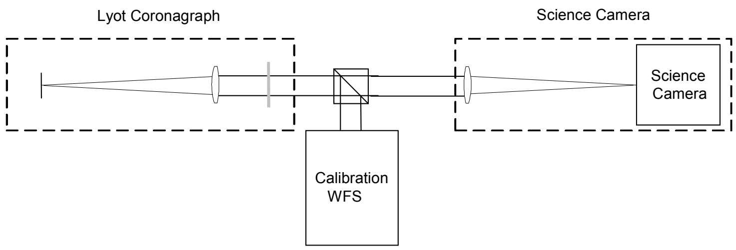


Figure 10: One possible arrangement of the calibration sensor imaging the Lyot plane

5.5.1 Relative and Maintenance Calibration Scenarios

The goal of the calibration routine is twofold: 1) to make a relative measurement of the wavefront between the CWFS and the wavefront seen by the science camera and 2) to maintain this wavefront during a period of observation. The wavefront is measured at the science camera in a fashion that optimizes the coronagraph performance. Here we plan to use techniques developed on the HCIT such as focus diversity and speckle nulling. The wavefront optimization is done by updating centroid offsets to the active wavefront sensor. Once satisfactory, the wavefront is measured with the calibration wavefront sensor. It is this wavefront sensor set point that will be used during the science observation. The maintenance calibration routine during a science observation consists of simply measuring the wavefront on the CWFS and providing updated centroid offsets to the active WFS. In this manner, the CWFS is proxy to the science camera wavefront.

5.5.2 Proposed Precision Wavefront Sensors

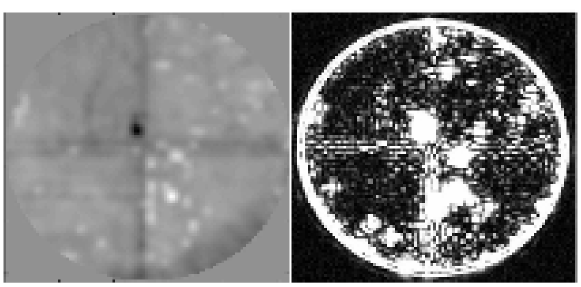


Figure 11: Illustration of the Lyot plane of a coronagraph used to sense phase. Left: Phase map of wavefront errors input to the coronagraph measured via focus diversity. Right: Actual image of the Lyot pupil plane, where phase errors have been transformed to intensity.

Using some fraction of the science light and re-imaging the pupil provides a very sensitive means of measuring the residual wavefront errors. Behind a Lyot coronagraph, intensity variations in the re-imaged pupil plane map (to first order) to phase-squared in the input pupil. (Green et al 2003a, 2003b). Because the coronagraph virtually eliminates diffraction, the optics occurring after the occulting spot do not act as a sensing bias. By modifying the set-point of the AO system, the pupil speckle intensities may be modulated and with enough diversity be characterized and corrected. We call this speckle nulling in the pupil plane. In a similar fashion, the CWFS may form a conventional image that permits speckle nulling in the image plane. In either case, the goals are to eliminate to quasi-static speckles that appear in the PWFS imagery (and hence the science imagery) by optimizing the set-point for the DM. These techniques are ideal in that they measure errors post coronagraph, but suffer from the need to dither, since they generally measure only the absolute value of phase. Team members at JPL have experimentally explored such methods using the Terrestrial Planet Finder High Contrast Imaging Testbed and the Palomar adaptive optics system.

We propose studying these techniques both analytically and numerically in order to determine the sensor that is most suitable for the high-contrast imaging from the ground. We will judge the proposed techniques against the wavefront calibration and maintenance requirements, and then rank them according to an ordered list of desired properties including cost, size, stability, photon budget, upkeep, and magnitude of needed dither/diversity. Where feasible in CoDR we shall test these techniques at JPL or UCSC to increase our technical understanding of engineering implementation. We will employ a decision matrix, weighting the desired properties for each method that meets the minimum requirements.

5.5.3 Phase-shifting diffraction interferometer (Sommargren, LLNL)

Absolute end-to-end metrology for the system will be provided by a LLNL-built Phase-shifting diffraction interferometer (PSDI). The PSDI (Sommargren et al 2002) was originally developed for optical measurements of the Extreme Ultraviolet Lithography (EUVL) system developed by a multi-institution consortium; it has been used to provide absolute measurements of the wavefront of individual aspheric optics and complete optical systems with 0.3 nm accuracy. The PSDI uses single-mode optical fibers illuminating micron-size pinholes to generate spherical wavefronts. One wavefront propagates through the optical system under test and then reflects off of a superpolished mirror surrounding the pinhole illuminated by another fiber, interfering with the wavefront emerging from the second fiber. The interference pattern falls on a CCD with no intervening optics. Figure 16 shows the PSDI layout in our ExAO testbed. By stepping through path delays between the two fibers, the phase can be measured in the interference plane, and then numerically propagated back to any plane in the system under test. Since there are no optics other than the fibers themselves, this provides an absolute (rather than relative) wavefront measurement. The fibers are compact and can be inserted at different parts of a complex optical system, providing extremely accurate and flexible metrology. Collaborator Gary Sommargren is the developer of LLNL's PSDI, and will work with us to exploit its truly unique capabilities. Our baseline incorporates a PSDI with an input fiber at the instrument input focal plane and the second fiber / superpolished mirror at the coronagraph input. The PSDI front end that feeds the fibers will be located off the telescope if possible. Key design issues include analysis of the achievable resolution and design of a fieldable PSDI suitable for an observatory environment.

5.6 Study of coronagraph concepts

(Oppenheimer, AMNH)

Amongst the competing coronagraph designs, the key issues to be addressed are the tolerance to errors (in both residual wavefront from the AO system and the stop itself), manufacturability of the required stops and inner working angle. The design study will investigate these issues in the context of the wavefront control, calibration and science instrument designs. The science requirement of an inner working angle of 0.1" drives the necessity to explore new designs as Lyot coronagraphs require inner working angles of several λ/D for high contrast. Smoothly varying apodizations allow additional degrees of freedom for solutions with improved performance. The Lyot project coronagraph(Section 8.4) will validate both the simulations and manufacturability of optimized stops. Efforts are already under way in the Lyot project to develop new methods for manufacturing apodizers with conventional optical fabrication methods. For example, a concave lens polished out of absorbing glass, sandwiched between an index-matched plano-convex lens is a readily manufactured apodizer with a profile close to a Gaussian.

5.7 Study of science instrument concept

(Doyon, UdM, Larkin, UCLA, Marois, LLNL)

The challenge of high-contrast imaging is essentially one of noise reduction. In the stellar neighbourhood of a point spread function (PSF), noise arises from: 1) photon noise, 2) atmospheric turbulence (speckle noise, Racine *et al* 1999), 3) light scattering by slowly evolving optical surfaces (quasi-static speckle noise) and 4) calibration errors (flat field noise, bad pixels , ghosts etc). Speckles, in particular, can mimic a science signal. We will design the ExAO system to minimize static wavefront error and hence quasi-static speckles, but completely removing these is difficult. A key feature of the ExAOC science instrument is the ability to retrieve a weak companion signal from PSF residuals left by the AO+coronagraph system. The efficiency of the science instrument as a speckle-suppressing device (SSD) can be expressed as a noise attenuation factor $\eta \equiv N/\Delta N$ where N is the original PSF noise and ΔN is the residual noise left by the instrument.

Most SSD concepts share the principle of acquiring multi-wavelength PSFs *simultaneously* and taking advantage of the deterministic behaviour of the speckle pattern with wavelength, and possibly the spectral characteristics of target planets, for discriminating speckles from a true companion signal. SSDs comes in various flavours: 1) multi-wavelength imagers (MWI) and 2) Integral Field Units (IFU). The MWI usually features a few (< 4) discrete wavelength samples (R~30-100) spanning a sharp spectral feature (e.g. methane at 1.6 μm) present in giant planets. Simple image subtraction is then used to reveal the companion signal. Since the speckle pattern magnifies with wavelength, this technique can also detect a featureless companion located at an angular separation larger than $\theta_c = \lambda^2/D\delta\lambda$ where $\delta\lambda$ is the wavelength difference between the reddest and bluest λ channels. The IFU works essentially under the same principle except that it provides a continuous spectrum over an arbitrary wide spectral range. A companion signal of arbitrary spectral shape can then be extracted using PSF subtraction algorithms *à la* Sparks & Ford (2002). Our study shall provide detailed trade analysis and feasibility of both approaches.

Experience with the 3-λ MWI camera TRIDENT on CFHT (C. Marois, 2004, PhD thesis, Marois et al 2003a) has shown that quasi-static speckles due to the instrument itself are by far the dominant source of noise (Marois et al 2003b). TRIDENT typically achieves attenuation η~3 in imaging (improving to η~10 with reference star subtraction.) Such modest attenuation is due to small non-common path aberrations between the three optical channels of the camera (Marois et al 2003b). Removing these aberrations is extremely challenging in multi-beam TRIDENT-like systems. Tiger-type IFU like OSIRIS (Larkin et al. 2003) and the IFU-based MWI device Multi-Color Detector Assembly (MCDA; Doyon et al. 2004, Marois et al. 2004), both intrinsically immune to differential aberrations, constitute our two strawman science camera concepts that we shall study in detail.

Key issues related to the science camera design study include:

- Determine the performance of dual-beam imaging system, MCDA and an IFU under the highly efficient ExAO coronagraph taking into account realistic differential aberrations.
- Identify technological risks (e.g. feasibility of micro-filters, micro-polarizers, etc)
- Develop performance simulation tools for predicting contrast ratio *vs* angular separation for different companion/parent spectra. This requires constructing realistic instrument models including signal extraction algorithms for assessing the relative merit of various concepts in terms of throughput, FOV, noise attenuation factor, spectral resolution, wavelength coverage and cost.

Our goal is to identify one "winning" instrument concept early in the study (by the mid-term review) and address the detailed design of one instrument in the remaining phase.

5.7.1 Multi-Color Detector Assembly (U. de Montreal, INO)

The MCDA concept, schematically illustrated below, consists of a micro-lens array aligned with a micro-filter array of 4 different wavelengths (1.52, 1.58, 1.64 and 1.68 μm) spanning the methane absorption. A cluster of 4x4 micro-lenses samples one λ/D yielding Nyquist-sampled images at 4 different wavelengths. Each micro-lens spans a cluster of 3x3 detector pixel to avoid spectral contamination from one wavelength to another. Such a device could be capable of speckle noise attenuation well in excess of 100. The MCDA would be located directly at a f/150 focus and would have a FOV of 6.3"x6.3 for a 2048x2048 detector. The MCDA can be designed to be deployable, allowing the flexibility to switch between broad band imaging and/or J- or K-band MCDAs. Another variant application would be a Multi Polarization Detector Assembly (MPDA) in which micro-filters are replaced by micro-polarizers (4 independent polarization states) to provide an efficient mean of extracting faint polarized signal (e.g disk) from a relatively bright (non-polarized) PSF. The MCDA has a wider FOV than an IFU, but much less spectroscopic flexibility and somewhat lower total efficiency due to the limited number of channels.

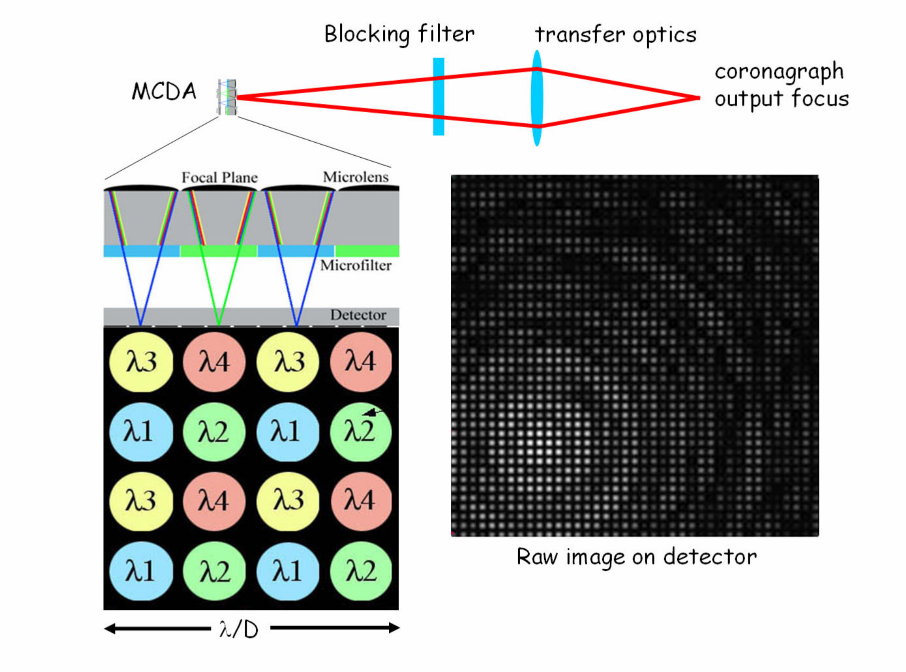


Figure 12: Schematic of the MCDA concept

5.7.2 IFU (UCLA)

A strong candidate for the science camera is an integral field spectrograph (IFU). Such an instrument is able to take thousands of spectra covering the adaptive optics target field. The result is that between 30 and 100 narrow band images, depending on the spectral resolution, are taken simultaneously over the entire field. Although several techniques have been used during the past decade to construct integral field spectrographs, we will initially concentrate on designs that use a lenslet array located in the focal plane (which has been reimaged after the coronagraph stop). Each lenslet concentrates the light into a small pupil image located one focal length behind the array. So the field is broken into an array of well separated spots that form the input focal plane for a traditional spectrograph. By rotating the dispersion axis of the spectrograph compared to the orientation of the lenslet array, the spectra can be made to interleave between each other and not directly overlap. In this way, spectra distributed over a rectangular field of view can share the same detector.

There are many benefits of an IFU as the ExAOC instrument. The most obvious is that you obtain a spectrum of each resolution element over the region of interest. This allows for the direct spectral classification of companions and the rejection of background stars. The large number of wavelength channels allows efficient speckle suppression even for objects with arbitrary spectra. Sensitivity is also quite high within an IFU since the optics can be relatively simple given the small field of view. Also, there are no slit losses that plague traditional spectrographs. At a resolution of 100 to 300, the detector is still background limited or close to it, so a broad band image can be formed by collapsing the spectral cube with very little noise penalty.

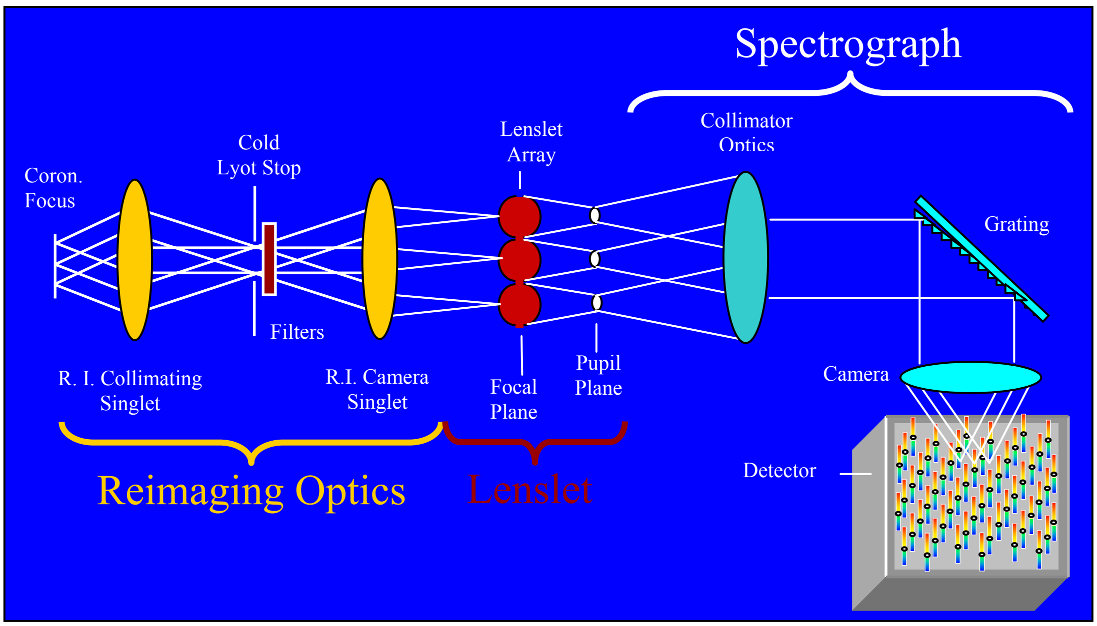


Figure 13: Schematic of a lenslet-based IFU

A lenslet based spectrograph has an important advantage over other IFU formats. It is one of the only techniques that samples the image plane early in the optical path. By separating different field points prior to the spectrograph, only the optics in front of the lenslet, typically simple reimaging optics, can degrade Strehl ratio or scatter light. Any errors in these optics will be common to all wavelength channels, giving a very high speckle suppression. On the other hand, combining the required spectral resolution, sampling, and field of view in a single instrument will be very challenging. We will explore the scientific requirements for resolution and the possibility of having an IFU with selectable FOV/resolution options.

5.8 Optomechanical design and flexure

(Cowley and Lockwood, UCSC)

ExAOC conceptual design will begin with a preliminary optical configuration. Initial tolerances are generated in the optical design. A support structure is generated to suspend the optical elements in space, and provide the required instrument-to-telescope mechanical interface. Analysis of the above design occurs on a component level as well as a system level as it evolves and boundary conditions are identified. Once the initial conceptual design coalesces to a point where it can be analyzed as a system, structural, thermal, and vibration analysis will be performed and evaluated. The analytical results are used as feedback to iterate the above process (including feedback to the optical design for reevaluation of simulated results). The goal is to gain reasonable assurance that the desired results are attainable.

The greatest concern in these systems is typically the stability of the non-common path elements. Support for this instrument will likely be some combination of optical "breadboards" carrying the modules, connected by a lightweight, stiff, low aspect ratio, frame (determinant truss structure). Athermalization will be required using some combination of low thermal expansion coefficient material, thermal strain canceling, and/or environmental temperature control. It will also be necessary to limit flexure with telescope rotation (either though structural optimization or active control). The design must put principal vibration modes above specified threshold and critical excitation concerns.

5.9 Reuse of existing designs

(Murowinski, HIA)

There are a number of areas where this instrument development has the potential to take advantage of designs which have heritage at Gemini and at other observatories. The advantages of doing so are evident. On the other hand, the cost of reusing a design can be significant, especially if one tries to fit a square design concept into a round requirement. During the design study, we will trade the reuse of candidate designs for subassemblies with that of developing new approaches. In general, preference will be given in the following priority: a) commercially available solutions, b) successful design solutions used on Gemini instruments, and c) successful design solutions used on other astronomical instruments.

Candidates for applicable designs used in other Gemini instruments are:

1. Altair software infrastructure,
2. GSAOI detector controller hardware architecture and software design,
3. Mechanical interface to ISS (which could be modeled on any of a few Gemini instruments: GMOS, GNIRS, etc.),
4. Cryocooler and cryocontrol from GSAOI,
5. Cryostat from NIRI/GSAOI
6. Electrical interlock circuits from GMOS/Altair
7. Altair atmospheric dispersion corrector

A substantial number of subsystems may be reused from non-Gemini projects, including (but not limited to)

1. An ExAOC IFU based closely on the OSIRIS Keck IFU
2. AO controller architecture based on the recently-upgraded Lick Observatory laser guide star AO system
3. Motion control systems from previous Keck instruments developed at UCO
4. MEMS control electronics used in 1024-actuator horizontal-path AO systems developed at LLNL
5. Calibration algorithms from the JPL high-contrast imaging testbed for Terrestrial Planet Finder

5.10 Simulations

(Poyneer and Macintosh, LLNL)

Verifying the performance of an ExAO system before construction is crucial and extremely complicated; as discussed in section 11.3, performance depends not on a single metric such as Strehl ratio but is defined by contrast vs. radius, depending on the spatial and temporal properties of many wavefront error sources and other sources of scattered light. Phenomena such as "pinned speckles" depend on both the coronagraph and AO system, and final sensitivity will depend on drifts in the optical calibration at the nm level. Simulations must run for an extremely long time – effects of small static wavefront errors may only become apparent on 10-60 minute timescales.

During conceptual design we will use a layered approach to simulations: (1) Analytic calculations of wavefront error power spectra, (2) Fourier-domain Monte Carlo simulations; and (3) Detailed physical optics simulations. We will also identify the feasibility of developing a tailored end-to-end simulation capable of long exposures during the PDR phase.

Analytic calculations follow the approach outlined in the error budget section 11.3 - evaluating the power spectrum and temporal properties of different wavefront errors. In the first weeks of the project we will update these simulations by combining the powerful PAOLA analytic simulation code developed by HIA with the ExAO speckle models developed by LLNL. These analytic tools can be used to rapidly explore system phase space.

Fourier-domain Monte Carlo simulations are a 2-dimensional stochastic version of the same approach, generating a series of independent phase error screens and applying a linear model of AO correction together with additional additive or nonlinear noise sources such as measurement noise, static calibration errors and temporal bandwidth errors. These simulations are computationally efficient and can be used to generate moderate exposure (minute to hour) PSFs for exploring coronagraph and instrument phase space.

Detailed physical simulations include all the key components of the AO system – wavefront sensor (spatial filter, lenslets, and CCD), deformable mirror model, control loop, frozen-flow atmosphere in one or more layers, telescope and coronagraph. Our current simulations are computationally expensive, requiring ~16 hours to generate a 1-second simulated exposure. However, they can be used to verify fundamental physical questions such as the performance of the SFWFS under real conditions (Poyneer and Macintosh 2004), effects of non-ideal deformable mirrors, etc. During the CoDR phase, we will refine our simulations by adding more physical effects such as scintillation and chromatic errors needed to populate the error budget. We will also develop simulation tools to study the AO optics as an integrated system, translating the results of finite element analysis into optical effects.

Ultimately, one would want to use not scaling laws but an end-to-end simulation to verify the long-exposure properties of an ExAOC system. Implementing a simulation is outside the scope of a conceptual design, but we will design and analyze the computational requirements of one during the CoDR phase. The long-exposure ExAO process can be parallelized temporally by splitting up the exposure onto separate processors, making it well suited to large parallel computers such as the facilities available at LLNL.

5.11 Integrated modeling effort

(Dunn, Herriot and Veran, HIA)

During the ExAOC Conceptual Design phase, HIA will undertake a study to assess the feasibility of producing an Integrated Model (IM) of the Gemini Telescope. The idea is that the IM would capture all the non-atmospheric effects, such as dome seeing, wind-loading, etc, that ExAOC will have to correct in addition to the atmospheric turbulence. This telescope IM will complement a integrated model of the instrument itself to prove, at the end of the Preliminary Design Phase, that the proposed error budget is attainable. Telescope effects typically induce distortions which are low spatial and temporal frequency but which are of high amplitude and, even after attenuation, might induce residuals that are too large. An IM of the Gemini Telescope will include CFD modeling of the Gemini dome and FEA modeling of the telescope structure. Experimental data collected at the telescope would allow confirmation of the validity of the model. However, the model will permit exploration the entire parameter space of which experimental data can only give a very partial description. As indicated in the budget, this effort is funded by HIA as an in-kind cost share to both the GLAO and ExAOC proposals.

5.12 Laboratory verification on the ExAO testbed

(Gavel, UCSC; Sommargren & Macintosh, LLNL)

Simulations can only go so far in exploring a complex phenomena like ExAO. In parallel with the Gemini effort we will carry out laboratory ExAO experiments in the Laboratory for Adaptive Optics (LAO, section 8.1). These experiments will be fully funded by the Moore foundation grant that established the ExAO laboratory.

The next phase of the testbed will be to implement a prototype spatially-filtered wavefront sensor (SFWFS). With the PSDI metrology we will be able to verify the SFWFS performance against an absolute standard. We will test the ability of the SFWFS to control the MEMS to the same level of flatness as achieved with PSDI, and the ability of both approaches to control simulated aberrations from phase plates. The absolute metrology will also allow a measurement of the aberrations in the wavefront sensor itself, the largest component of non-common-path aberrations.

During the PDR/CDR phase, the Moore foundation grant will continue to fund the testbed. We will construct an end-to-end testbed resembling the full ExAO layout, with reimaging optics and a coronagraph for testing of control and calibration algorithms, component testing, and tests of the effects of optical flexure and temperature changes.

Meanwhile, we also have access to the JPL HCIT (section 8.3), which will be used to test calibration (section 5.5), and will provide us with data on the performance of the Xinetics mirrors (section 5.5).

5.13 Development of I&T plan

(Murowinski, HIA, and Macintosh, LLNL)

A product of the conceptual phase will be a workplan for the execution of the instrument, including detailed design, fabrication, testing and delivery. Plans on how that work will be organized are still very broad at this proposal stage, but we expect to structure that work along the following general principles.

The concept design phase should result in a better understanding of how to partition the development of the instrument between those institutions participating in the next phase of development. That partitioning will divide up components of the instrument (rather than fields of responsibility) and be based on expertise and history of each group, cost effectiveness, and finding clear verifiable boundaries between the work packages. During the detailed design phase we expect a large interchange between the groups to continue, as designs are shared and developed. During fabrication phase, each group would be responsible to build, qualify to final standards, and deliver their component(s) to the integration center.

System integration, test and delivery would follow a series of clear steps: a) integration, alignment and functionality test, b) performance test and characterization using realistic simulated aberrations, c) environmental tests – for temperature, gravity vector, etc., d) science simulation tests and characterization, e) acceptance tests to the agreed ICDs and FPRD, f) packing, shipping to the telescope, post-shipment tests, and finally g) installation, final acceptance and commissioning. The key goal will be to fully verify that the ExAOC system reaches its design contrast with realistic simulated aberrations in a laboratory setting before shipment to an observatory.

6 Management

The proposed ExAOC Conceptual Design Study will be performed by an international, multi-institutional team that has been assembled with the explicit goal of including the premier, relevant, technical talent that is available throughout the Gemini member countries. We believe this has enabled us to assemble a team that is uniquely qualified to design and ultimately to construct, test, and deploy the proposed instrument, which is well beyond the current state of the art, with the minimum possible technical risk. However, careful attention will be needed to manage this multi-institutional team effectively to achieve the overall project objectives within the applicable schedule and budget constraints. Therefore, in order to minimize the associated programmatic risk, we will employ a variety of management "best practices" which are drawn from our collective experience in coordinating large, collaborative, technical, research and development programs.

The basis of our program management strategy can be encapsulated by the following general guiding principles: 1) organizational commitment to strong project management, 2) clear definition of institutional responsibilities, objectives and interfaces, 3) proactive communication between institutions.

The most important aspect of our program management strategy is the central project leadership role played by the project manager. The ExAOC project will be led by the combination of the Principal investigator, Bruce Macintosh, and the Project Manager, David Palmer. The organization chart (Figure 14) shows that all aspects of the program flow through this executive management team. As is consistent with recognized best practices for this type of project, the Project Manager has overall responsibility for achieving the project deliverables, while the Principal investigator has the ultimate responsibility for ensuring that the project deliverables satisfy the overall scientific and technical objectives of the program. Two other project members will participate in high-level decision making. The Project Scientist, Prof. James Graham, will provide the PI with substantial advice and support on scientific and technical matters and serve as the interface to the science team. Similarly, the systems engineering lead, Richard Murowinski, will define interfaces and track Gemini documentation such as the FPRD. Neither, however, will have direct program management responsibility except for their respective subteams.

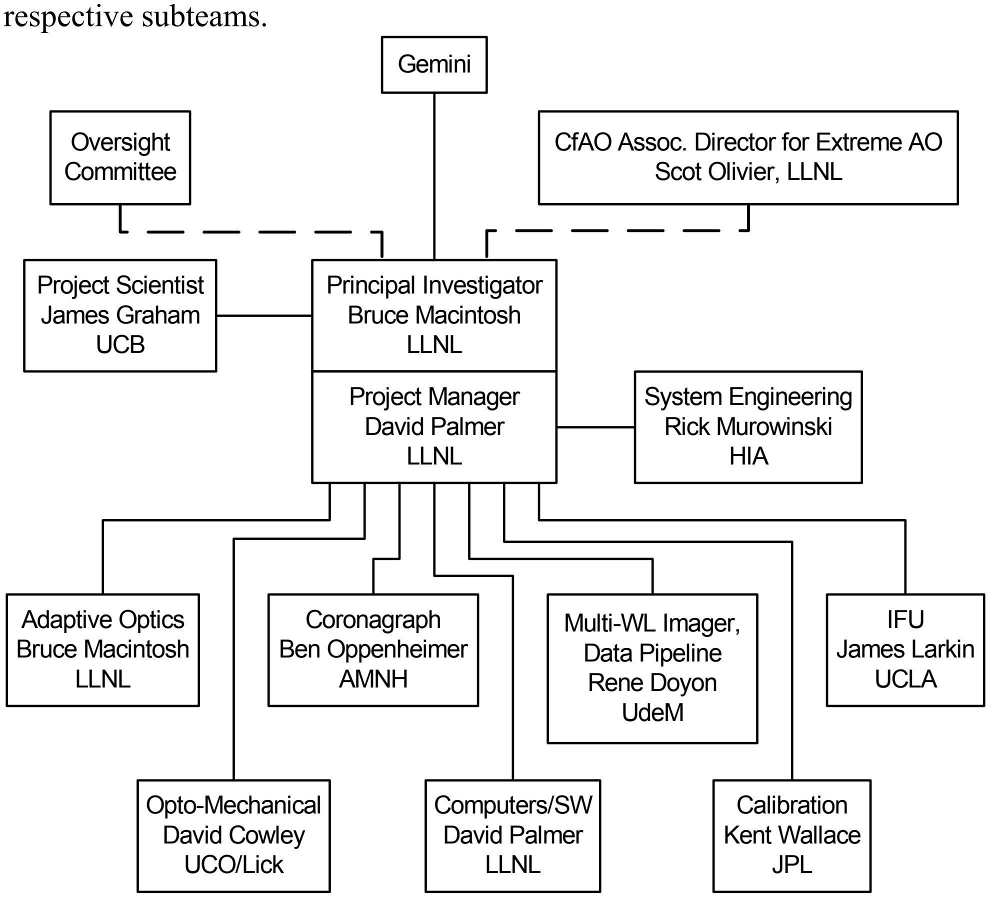


Figure 14: Organizational chart for the ExAOC conceptual design study phase.

During the construction phase we will adopt a more hierarchical organization chart, with reporting passing through major subsystem leads, but during the design phase we prefer the efficient communication of this relatively flat organization.

In addition to the central organizational role played by the ExAOC Project Manager, several other organization elements will support the overall commitment to program management best practices. First, to insure that the ExAOC project has the requisite level of institutional support, including access to all necessary institutional resources, letters of commitment are being obtained from upper management at each institution. Second, each institution participating in the project will identify an institutional project leader who will serve as the primary point of contact with the ExAOC Project Manager, and who will be responsible for tracking and reporting progress on project milestones and deliverables at their respective institutions [In the case of the two Canadian institutions, a single point of contact at HIA will be responsible for tracking and reporting progress for both institutions, and HIA will manage all Canadian subcontracts]. Third, an ExAOC oversight committee, consisting of a select group of senior scientists/engineers/managers from participating institutions, is being assembled. The ExAOC oversight committee will be chaired by Dr. Scot Olivier, and will be briefed bimonthly via video/tele-conference by the ExAOC executive management team, and will provide written feedback to the ExAOC Project Manager. Members of the ExAOC oversight committee will also be invited to attend the three project-wide meetings. Fourth, as required by AURA program management guidelines, written project progress reports will submitted to AURA by the fifteenth day of each month.

Our second guiding principle for program management, the clear definition of institutional responsibilities, objectives and interfaces, will also be implemented using recognized technical management best practices. First, the work expected from each institution for the ExAOC Conceptual Design has already been well defined in a detailed work breakdown structure (WBS) and the associated schedules and budgets that have been prepared as part of this proposal process. The WBS also contains information about any linkages between project tasks, which highlights the interfaces to be managed as the project proceeds. Once the project begins, the ExAOC Project Manager will work with each institutional lead to review, refine and then actively track the project milestones and deliverables. A baseline of 4 intermediate milestones will typically be established for each subsystem to ensure that progress can be adequately evaluated at each institution throughout the project time frame. Systems engineering provided by HIA (Section 6.2) will define interfaces between subsystems.

The third program management guiding principle, proactive communication between institutions, will be accomplished primarily through the recognized best practice of a regular, hierarchical meeting schedule. First, there will be three face-to-face, multi-day, project-wide meetings through the course of the Conceptual Design: 1) an ExAOC kickoff/workshop, 2) a midterm review, 3) a pre-CoDR review. Second, on the months when there are not face-to-face meetings, there will be project-wide internal status reviews via video/tele-conference between the leadership and the senior team members of each subproject. Third, when there are no scheduled project-wide meetings, the ExAOC executive management team will hold weekly video/tele-conferences with the institutional project leaders. Fourth, an ExAOC project web site will be maintained to support dissemination of technical and administrative information. Finally, the CfAO will dedicate a teleconference line to the project, to be available at any time for ad-hoc multisite discussions. The CfAO has considerable experience managing a distributed collection of collaborative researchers and we are confident that these proactive project communication structures will provide the requisite flow of information between the participating institutions and the executive management team to enable timely assessment of project progress and early identification and mitigation of any problematic technical, schedule or budgetary issues.

6.1 Synergy with the Center for Adaptive Optics

The Center for Adaptive Optics (CfAO) is an NSF Science and Technology Center that seeks to advance the state-of-the-art of adaptive optics in the fields of astronomy and vision science. Founded in 1999, with headquarters at the University of California, Santa Cruz, the CfAO has an annual budget of ~$4M that supports activities at member institutions, including 11 university nodes and 10 national laboratories and observatories. CfAO technical research and development activities are focused in 3 Themes: 1) adaptive optics for extremely large telescopes, 2) extreme adaptive optics (ExAO), 3) vision science instrumentation. The primary goal of the ExAO Theme is to facilitate achievement of the high-contrast imaging and spectroscopic capabilities needed for direct characterization of extrasolar planetary systems and their precursor disks.

Since November 2002, the core project sponsored within the CfAO ExAO Theme has been the "eXtreme Adaptive Optics Planetary Imager (XAOPI)" project, led by Bruce Macintosh. The XAOPI project, along with earlier technical activities supported by the CfAO within the ExAO theme since Nov. 2001, has laid the groundwork for the Gemini ExAOC project by exploring key technical and scientific concepts of a straw man design for an instrument on an 8-10 meter telescope, capable of directly detecting and characterizing Jupiter-like planets around a significant sample of nearby, young stars. Moreover, during the period of performance for the ExAOC Conceptual Design Study, the XAOPI project will continue to provide significant synergistic support for many of the institutions participating in the ExAOC project, enabling the completion of a significantly more comprehensive design study than would otherwise be possible utilizing Gemini funds alone. The distribution of support for CfAO-funded and ExAOC conceptual design tasks is tabulated in the budget detail shown in Section 9.

In addition to the technical synergy, the CfAO will provide significant management synergy for the ExAOC project. The XAOPI project has already been organized within the CfAO ExAO Theme to distribute work among multiple institutions with the relevant expertise, and to monitor progress, and track the budget and schedule, milestones and deliverables at those multiple institutions. CfAO employs a full time financial analyst and a Managing Director to help the Theme Leaders and the Project Managers to accomplish the necessary program management functions. In addition, the CfAO provides several layers of oversight, including the CfAO Executive Committee, Program Advisory Committee, External Advisory Committee, and Oversight Committee, along with the NSF Program Manager and Annual Site Visit Committee. The roles and responsibilities of all of these layers of oversight have been carefully tuned for optimal effectiveness over the 5 years that the CfAO has been in operation, and there has been substantial evolution since the beginning of the Center, which we believe has resulted in a highly effective oversight structure for the Center. For the ExAOC project, all of these CfAO management structures will be in place to monitor both the portion of the relevant technical work being carried out under the auspices of the CfAO, as well as, when appropriate, the work being carried out with direct ExAOC funding, and the overall combination of this work – to ensure all relevant tasks are being performed in a suitably integrated manner. Furthermore we will work closely with AURA to ensure that these all these CfAO management structures complement those specifically and additionally instituted for the ExAOC project.

In addition to the significant synergy with the CfAO ExAO Theme, the ExAOC project will benefit substantially from the related work supported by the Laboratory for Adaptive Optics (LAO) at the University of California, Santa Cruz (UCSC). The LAO is operated by the UC Observatories in partnership with the Center for Adaptive Optics. Claire Max is the principal investigator. Jerry Nelson (CfAO Director) and Joseph Miller (UC Observatories Director) are co-investigators. The purpose of the Laboratory, which was recently established with a $9.1M grant from the Gordon and Betty Moore Foundation, is to take new adaptive optics ideas from the concept phase to working prototypes and fielded astronomical instruments. In particular the LAO will serve as the main facility within the UC system for testing concepts for ExAO and AO for extremely large telescopes.

In the area of ExAO, experiments using LAO equipment, particularly an interferometer developed at LLNL that is capable of measuring optical aberrations with absolute accuracy at better than the nanometer level, have already established an experimental baseline for the wavefront accuracy required to achieve image contrast similar to ExAOC design goals. In the future, the LAO is intended to support an increasingly complex series of tests to further investigate fundamental optical science issues related to the successful development of an ExAO instrument for a 8-10 meter telescope, and ultimately, the LAO is intended to provide a venue for the integration and testing of an ExAO instrument, such as the Gemini ExAOC. Thus, all of this work supported by the LAO will have direct impact on the ExAOC project, and in particular in the ability of the project team to mitigate technical risk and defray costs associated with the development of required optical science infrastructure. This is clearly a huge advantage for the successful execution of the ExAOC project.

6.2 Systems engineering

Due to the high level of technical complexity and the need to meet the standards for a conforming Gemini facility instrument, the ExAOC project will need careful adherence to rigorous system engineering practices. As co-PI, the system engineer for the design phase, Rick Murowinski, is in a position to enforce these practices. The geographically distributed nature of teams participating in this project does present a challenge, but one which is common in large instrumentation projects today. It has been amply demonstrated that a distributed team will achieve equal technical success to a nuclear team if the work and interfaces are well managed, and indeed often a greater success if the work distribution takes advantage of natural synergies. It is our hope and belief that we will deliver a better instrument to Gemini than any one of our partners could have done on their own.

As described elsewhere in this proposal, we will make use of error budgets to ensure a balanced distribution of technical specifications among the subsystems, to achieve a whole which meets the overall requirement with least overall cost. Error budgets, although often created top-down, will be iterated with designers of components and subsystems toward a budget which distributes the technical challenge as uniformly as possible without overdesigning components or subassemblies. Development of enabling technologies, including those described above, will be formally tracked through the design phase, making use of decision points and alternative plans when called for. An early task in the conceptual design phase will be to study all applicable existing ICDs to ensure all interfaces needed for ExAOC are described or are identified for development. The design study will result in an ICD table identifying applicable ICDs and listing those needing development during preliminary design.

An important function of system engineering is to achieve closure between the performance of the delivered instrument and the expectations of the user. Development of the ICDs, OCDD and FPRD should result at the end of this design phase in a clear description of the instrument being taken to the detailed design phase of the project. At the same time, it is important to develop tools which allow us to model that the instrument described in those documents is both realizable and will meet the performance requirements. The measures of confidence in technical realization are had through the error budgets and whether existing, affordable technology exists to meet each element of those budgets, and through the tracking of enabling technology. The measures of performance at this stage of development come through models (section 5.10). We will develop and use a layered set of simulations of varying fidelity to give us confidence in some critical requirement areas. We will also develop a framework and development plan for broader and more detailed performance models which can be built and validated in the next phase of the project and be used to inform and validate design decisions through the rest of the development cycle.

6.3 Effort and budget tracking

The ExAOC Project Manager (PM) will have overall responsibility for tracking the effort and budget expended during the project, as well as continually ensuring that adequate technical progress is being made on each task, and that milestones and deliverables are being met on time and on budget. To enable the PM to meet these responsibilities, proven, existing effort and cost accounting and reporting structures will be utilized at all partner institutions.

As summarized in Section 9, the bulk of the direct Gemini funding for the ExAOC Conceptual Design Study will be used to support activities at the Canadian institutions with a smaller amount going to UCLA for one of the science instrument designs. The effort and budget expended by the Canadian collaborators, including institutional direct matching funds, will be tracked by HIA, with monthly reports to the overall project manager at LLNL. HIA's Astronomical Technology Research Group in Victoria (ATRG-V) is a mature project-based group with well-established formal project management processes. As a matter of standard operating procedure, staff effort and expenditures at HIA are tracked with our corporate resource tracking and reporting system, SIGMA. Project schedule and budget tracking for the Canadian component of ExAOC design study will be done at HIA with Microsoft Project, using a project plan which has been tied at key milestones to that of the rest of the collaboration by the ExAOC Project Manager, and making use of information provided by SIGMA as well as University de Montreal and subcontractors. The Canadian Project plans will be updated regularly with current task status, budget, and resource requirements, and necessary adjustments made to ensure project deliverables are completed on time and on budget, and that revised project plan delivered to the ExAOC Project Manager.

For portion of the direct Gemini funding going to UCLA, the effort and budget expended there will be tracked in conjunction with the standard practices developed for the CfAO. Under these practices, financial and effort expenditures are obtained using the existing UCLA accounting system, and this information is reported to the CfAO financial analyst on a quarterly basis. The ExAOC PM will have access to this information as soon as it is reported to the CfAO, and will use it to monitor activity at UCLA.

Also as summarized in Section 9, several sources of external funding will be used to support specific and distinct elements of the technical and management activities that will be necessary to produce the completed ExAOC Conceptual Design. The major sources for this funding are the CfAO, including the LLNL CfAO matching funds, and the Moore Foundation grant for the LAO. The ExAOC Project Manager will also track the budget and effort expenditures for these funds using the proven, existing accounting and reporting procedures.

The bulk of the CfAO funding (and the LLNL matching funding) is being used to support activities at LLNL, which are tracked and reported monthly by the LLNL cost accounting system. These reports will be available to the ExAOC PM every month.

Other institutions receiving CfAO funding relevant to the ExAOC Conceptual Design are JPL and STScI. These institutions provide tracking data, derived from their existing institutional accounting systems, to the CfAO financial analyst on a quarterly basis, and this information will be available to the ExAOC PM as soon as it is received by the CfAO.

Expenditures of Moore Foundation grant funding is being used to support technical and management activities at UCO/Lick, and is being tracked using the existing UCO/Lick Business Office accounting system. This system generates monthly reports that will be made available to the ExAOC PM.

By utilizing the data generated and reported by all of these proven, existing institutional accounting systems, the ExAOC Program Manager will have all the necessary information to track effort and budget expenditures at each collaborating institution. Combining this with the rigorous program management practices discussed above in Section 6.1, including the detailed Work Breakdown Structure that ties together all elements of the project, the ExAOC PM will be able to achieve the overall project management goals, and minimize programmatic risk.

7 Team members and roles

Here we give brief descriptions of the capabilities and roles of the institutions and key personnel involved in the project. For personnel with detailed tasks in the WBS, we list the total effort over the duration of the project. (Many additional personnel such as technicians and programmers appear in the WBS. We do not list effort for personnel with primarily oversight roles.)

7.1 Lawrence Livermore National Laboratory

LLNL's roles are to provide leadership for the program, develop system performance models and error budgets, and develop the realtime AO control architecture. (UCSC serves as the administrative prime contractor due to its lower overhead structure; Bruce Macintosh has a multi-location appointment between UCSC and LLNL.)

The AO group in LLNL's I division has played major roles in the development of seven AO systems, including the Lick and Keck astronomical systems, three AO systems for vision science (two MEMS-based), AO for high-energy lasers, and a thousand-actuator MEMS AO system for communications. LLNL is the leading institution for AO technology development in the NSF Center for Adaptive Optics.

Bruce Macintosh is the Principal Investigator. He obtained his Ph.D. at UCLA working as deputy project scientist on a dual-beam infrared camera for Lick Observatory (named, appropriately enough, "Gemini".) He is now a physicist at the Lawrence Livermore National Laboratory and also holds a joint appointment with UC Santa Cruz. Dr. Macintosh is uniquely qualified to lead the ExAOC project. He is an expert in the direct detection of extrasolar planets leading or collaborating in three such searches with the Keck AO system since 2000. During these searches he has modeled the performance of the AO system to understand what factors (e.g. static primary mirror errors) limit the high-contrast performance. He has considerable experience in developing and using adaptive optics and infra-red imaging instrumentation, with involvement in both the Lick and Keck AO system development and characterization. In 2002-2003 he led a CfAO project to characterize and improve the performance of the Keck AO system that has resulted in an increase in H-band Strehl ratio from 0.25 to 0.4. He is the lead for ExAO studies on the Thirty Meter Telescope project. He originated the spatially-filtered ExAO wavefront sensor that ExAOC will use, and developed the error budget methodology shown in section 11.3. Furthermore, since November 2002, Dr. Macintosh has served as the Principal investigator for the "eXtreme Adaptive Optics Planetary Imager (XAOPI)" design study project, the core project sponsored by the NSF Center for Adaptive Optics (CfAO) within its "Extreme Adaptive Optics (ExAO)" theme. Dr. Macintosh will provide overall leadership to the team, and develop error budgets and system performance models and goals. (26 weeks effort.)

David Palmer is the Project Manager and also the lead realtime control engineer. Mr. Palmer also brings excellent qualifications to the role of ExAOC Project Manager. He has over 14 years of technical and administrative management experience, most recently managing a successful, multi-year, multi-million-dollar, inter-disciplinary project to develop an infra-red gas analyzer. He is also a technical expert in real-time control systems, with specific experience in state-of-the-art adaptive optics, having recently completed an upgrade of the control system for the Lick

Observatory adaptive optics system, which remains the world's only adaptive optics system with an operational sodium-layer laser guide star facility. In addition to his primary responsibility as ExAOC Project Manager, he will lead the ExAOC real-time control system development. Mr. Palmer also serves as a Group Leader in the LLNL Computations Directorate, which is one of the country's premier scientific computing organizations (29 weeks effort.)

Brian Bauman has been an optical instrumentation engineer at LLNL since 1995. He has worked on the Lick Observatory LGS AO system, development of AO for TMT/CELT, and on two AO systems for vision science. He will be responsible for the ExAOC optical design. He also consulted on the Gemini laser guide star BTO system. (10 weeks effort.)

Christian Marois is completing his Ph.D. at the University of Montreal and will be coming to LLNL as a postdoctoral researcher in May 2004. His Ph.D. thesis involved building the TRIDENT multiwavelength camera and analyzing the factors that determine the efficiency of multiwavelength speckle suppression. He will work on the comparative analysis of the MCDA and IFU concepts and on incorporating multiwavelength imaging into ExAO noise models.

Scot Olivier is the Adaptive Optics Group Leader in the LLNL Physics and Advanced Technologies Directorate, and also serves as an Associate Director of the NSF Center for Adaptive Optics with responsibility for the Extreme Adaptive Optics Theme. In addition, Dr. Olivier is currently Chair of the SPIE International Technical Group on Adaptive Optics. He will assemble and chair the ExAOC oversight committee.

Lisa Poyneer has a ME in electrical engineering from MIT. She developed the Fourier Transform Reconstructor and co-developed the spatially filtered wavefront sensor that ExAOC will use. She is responsible for wavefront reconstruction algorithms and simulation development. (17 weeks effort.)

Gary Sommargren obtained his Ph.D. in optics at the University of Rochester in 1972. He developed the phase-shifting diffraction interferometer (PSDI) that provides sub-nm absolute metrology for the Extreme Ultraviolet Lithography program run by a consortium of national laboratories and semiconductor manufacturers. He is one of the world's experts in precision optical measurement. He will provide consulting for the development of the ExAO testbed and the calibration wavefront sensor. (2 weeks effort)

7.2 UC Santa Cruz / UCO/ CfAO

UCSC, the home of the NSF Center for Adaptive Optics (CfAO), will be the prime contractor. The UC Observatory (UCO) shops will be responsible for the optomechanical engineering of the system and the development of the overall software architecture. UCSC is also the location of the ExAO testbed. CfAO will host most project-wide meetings.

The UCO shops are one of the leading astronomical instrumentation groups in the world; recent instrument projects include DEIMOS, ESI and HIRES for the Keck observatory.

David Cowley received his degree in Mechanical Engineering at University of British Columbia, and was Operations Engineering group leader for the Canada France Hawaii Telescope before joining UCO/Lick Observatory as Chief Engineer and Technical Facilities Manager in 1993. He has acted as Project Manager for the following projects: Multi-Object Spectrograph (MOS) on the Shane 120" at Lick Observatory, Echellette Spectrograph and Imager (ESI) on Keck II, and

Deep Imaging Multiobject Spectrograph (DEIMOS) on Keck II. Mr. Cowley is currently Project Manager for the HIRES CCD Upgrade, and the Atmospheric Dispersion Corrector (ADC) to be installed on Keck I. He will manage the UCO optomechanical effort for the project. (3 weeks effort)

William Deich has worked at UCO/Lick Observatory since April 1996. He provides the lead technical support for Lick Observatory and is presently serving as supervisor of the Scientific Programming Group. The majority of his software development has centered on data-acquisition systems, messaging systems, motor controls, and GUI development. His most recent projects include the control software for an atmospheric dispersion compensator for the Keck-1 telescope (ongoing), and for the instrument rotator for the DEIMOS instrument at Keck. He will lead the software architecture development and component control. (11 weeks effort)

Don Gavel obtained his Ph.D. in electrical engineering at UC Davis in 1988. He is the director of the Laboratory for Adaptive Optics at UCSC. He came to UCSC with more than 12 years of experience in adaptive optics at LLNL, most recently as the lead for the facilitization of the Lick Observatory laser guide star system. He will supervise the development of the ExAO testbed and work on AO control algorithms, particularly predictive control.

Christopher Lockwood obtained his degree in Mechanical Engineering at California Polytechnic Institute. Before joining the Lick team in 2001, he was Lead Engineer at NASA AMES for the Internal Wind Tunnel Balance Lab. Here at Lick, he has worked on the Shane 3-meter Hydrostatic bearing analysis, Lick Guide Camera design, Dewar 8 tantalum shield/3-axis tilt retrofit, Lick AO bench encoding/control upgrade, and the Dewar design for the upcoming Automated Planet Finder telescope. Mr. Lockwood is the lead engineer for the ExAOC optical design. (13 weeks effort)

Andrew Sheinis obtained his MS in optics in 1985 and a Ph.D. in astronomy at UCSC in 2002. He was project engineer for the ESI instrument at Keck. He will translate the optical designs and error budgets into mechanical tolerances for the optomechanical engineering effort.

7.3 Hertzberg Institute of Astrophysics

HIA is the second major partner (after the CfAO) in the project, and the lead institution for all Canadian participation. HIA is one of the institutes of the National Research Council of Canada, and work for astronomical instrumentation is carried out at HIA by the Astronomy Technology Research Group - Victoria (ATRG-V), led by Dr. David Crampton. HIA has responsibility for systems engineering, particularly interfaces with the Gemini observatory, and development of the software interface between ExAOC and Gemini. HIA will also develop AO control algorithms.

Recent major projects at HIA's ATRG-V include the Altair adaptive optics system. The Gemini Multi-Object Spectrographs (GMOS-North and GMOS-South) were developed in collaboration with UKATC. ATRG-V provided system engineering, prefocal plane assemblies, optics and some software components including the original software design; ATRG-V also carried out a MCAO LGS WFS Conceptual Design Study, and provided camera hardware for the Gemini Facility wavefront sensors. HIA also developed the PUEO adaptive optics system (CFHT) in collaboration with France; ATRG-V provided optomechanical and WFS design and hardware while France developed the software. ATRG-V is leading the James Web Space Telescope Fine Guidance Sensor and Coronagraphic Imager (FGS-G and FGS-TF), which is being developed in collaboration with Canadian industry, with science and system engineering led at HIA while the detailed design and fabrication are being performed in industry. Finally, ATRG-V is also leading Canadian engineering effort in the Thirty-Meter Telescope development (TMT).

Rick Murowinski, who will act as Canadian co-PI for the ExAOC work and lead the systems engineering effort, was Project Engineer and Canadian Project Manager for the GMOS Spectrographs collaboration. He is also deputy Group Leader for the ATRG-V, and System Engineer for the JWST Fine Guidance Sensor / Coronographic TF Imager. (11 weeks effort.)

Jennifer Dunn leads the instrumentation software team at HIA. She is also the interim manager for the Integrating Modeling Task Group for the TMT project. Ms. Dunn coordinated and developed a robust control system for Gemini's Adaptive Optics instrument, Altair. She was also involved in the coordination and leadership of the GMOS pre-focal plane software development, development of the GMOS Nod and Shuffle software and prototyping of the GMOS Mask-Making software. She will lead the development of the software interface between Gemini and ExAOC. (10 weeks effort.)

Jean-Pierre Véran is the team leader of the AO Group at HIA. He was the AO engineer / scientist for Altair, and was also involved the integration, test and commissioning of PUEO. He is now member of the TMT AO Working Group. His area of expertise includes AO modeling, wavefront estimation, AO system design / engineering, AO observations and AO data processing. He will lead work on AO control algorithms for ExAOC. (13 weeks effort.)

7.4 American Museum of Natural History / Space Telescope Science Institute

Ben Oppenheimer at AMNH, together with collaborators, has lead responsibility for development of the ExAOC coronagraph, including modeling and possible prototyping. This team has recently deployed the world's first high-order AO diffraction-limited, optimized coronagraph, a part of the Lyot Project. The Lyot Project coronagraph was successfully commissioned at the US Air Force Advanced Electro-Optical System this March and is already generating new data in the regime of very high-order AO coronagraphy, with H-band (1.65 micron) Strehl ratios > 0.8 (Perrin et al. 2003). This is the only system can test the issues and complications of placing a relatively extreme AO system in front of a purpose-built coronagraph that is comparable to the proposed system for Gemini. The Lyot Project coronagraph uses an AO system with 10 cm subapertures, the finest wavefront sampling available. The instrument was built with an imaging precision unsurpassed in coronagraphs to date, with an end-to-end wavefront error of better than 30 nm RMS (a factor of two better than the design spec).

Ben Oppenheimer, is a research fellow at the department of astrophysics at AMNH. The PI of the Lyot Project, he has worked on three different coronagraphs, including the Hopkins AOC which he used to image Gliese 229B for the first time, the Palomar AO system in conjunction with Cornell's PHARO camera, which he used with Sivaramakrishnan to conduct the first quantitative investigation of coronagraph performance behind an AO system, and finally the Lyot Project coronagraph, designed from scratch and built in the American Museum of Natural History's new Astrophysics Laboratory, devoted solely to exoplanetary science technology. He will lead the coronagraph effort, and serve on the science team, particularly in the area of evaluating requirements for planet characterization. (9 weeks effort.)

Andrew Digby is a Michelson fellow at the American Museum of Natural History. He is an expert on proper motion studies and stellar populations, and led the Lyot Project software development and optomechanical alignment. He will work on development and evaluation of coronagraph technologies. (1 week effort.)

Anand Sivaramakrishnan is the co-founder of the Lyot Project, and the JWST Wavefront Sensing and Control scientist at Space Telescope Science Institute. He advanced both the theory of high order AO coronagraphy on ground-based telescopes, and the structure of the high Strehl ratio PSF. He pioneered AO coronagraphic simulations that matched actual AO data, and worked on Palomar AO system development. He will lead the coronagraph simulation effort. (12 weeks effort.)

Russell Makidon is on the staff of Space Telescope Science Institute. He developed Lyot Project ExAO coronagraphic simulations to support instrument design, as well as more general design optimization methods for EXAO coronagraphs. He will implement coronagraph simulations and dynamic range assessment of coronagraph designs. (6 weeks effort.)

Remi Soummer is a Michelson fellow at Space Telescope Science Institute. He invented apodized pupil Lyot coronagraphy, extended phase-mask coronagraphic concepts, and developed ExAO simulations for the ESO VLT Planet Finder study. He is an expert on speckle statistics, and is working on an apodized pupil design for the Lyot Project. He will work on coronagraph simulations. (3 weeks effort.)

7.5 University of Montreal Laboratoire d'Astrophysique Expérimentale (LAE)

The LAE has a long experience in the design and construction of infrared instrumentation both for the 3.6m Canada-France-Hawaii telescope (CFHT) and the 1.6m Observatoire du Mont Mégantic (OMM). Instruments delivered to CFHT include: KIR, a 1024x1204 high spatial resolution 1-2.4 μm camera for the adaptive optics bonnette and CFHT-IR, a 1-2.4 μm facility IR camera. The LAE is responsible (INO as sub-contractor) for the optics package of WIRCAM, a wide-field IR camera for CFHT featuring one of the largest cryogenic refractive optics in the world.

University of Montreal will be responsible for studying multi-wavelength imaging techniques, particularly the MCDA concept, and in helping to model multi-wavelength speckle suppression. They will also specify the data pipeline.

René Doyon is astronomer and group leader of the Laboratoire d'Astrophysique Expériementale (LAE) of the Université de Montréal devoted to astronomical instrumentation development. He led the development and construction of three facility infrared cameras for CFHT (KIR, CFHT-IR and the Wide-Field Infrared Camera WIRCam), and more recently, the first differential imaging camera TRIDENT. He will lead the multi-wavelength-imaging and MCDA effort, and serve on the science team. (4 weeks effort.)

René Racine is an astronomer and professor emeritus at the Université de Montréal. While CFHT Director (1980-84) he pioneered the improvement of image quality at large telescopes. He built the first astronomical "AO system" (CFHT's HRCam, 1987) and contributed to a number of AO projects, notably CFHT's PUE'O and Gemini's Altair for which he was a Project Scientist. Father of the TRIDENT concept, he was the first to underscore and quantify the problems associated with speckle noise in high-contrast imaging.

7.6 Institut National d'Optique (INO)

The National Optics Institute (INO) is a private, non-profit corporation founded in 1985. Over two hundred people are employed at its facilities in Canada. INO areas of expertise include advanced coating development, astronomical camera designs and micro-optics. INO recently delivered a pupil apodization mask for a coronagraph project in Europe. INO will be responsible for the engineering of the multi-wavelength and MCDA effort and will assist for engineering trade studies.

Simon Thibault is a program manager (Optical Design) at INO and an Associate Professor at Laval University. He is an expert in optical design, responsible for many astronomical projects including the optical design and optics procurement for WIRCAM, a camera featuring one of the largest cryogenic optics in the world. He is also project manager for several INO projects including advance coating development for JWST (dichroics, wide-band etalon coatings, IR filters), durable coating for VLOT and micro-optics. M. Thibault will lead the INO portion of the MCDA effort. (30 weeks total INO effort.)

7.7 Jet Propulsion laboratory

JPL has a long heritage in adaptive optics and precision optical systems. The JPL-built Palomar facility AO system PALAO achieves K Strehl ratios >0.75 and operates at up to 2 kHz. JPL also led the construction of the Keck interferometer, which combines light from the world's two largest optical telescopes into the equivalent of a single 85-meter telescope. Recently, the Keck Interferometer has observed the inner regions of the galaxy NGC 4151, revealing the finest level of detail in a galaxy ever produced at infrared wavelengths. Keck's nulling mode will soon allow detection of extrasolar zodiacal clouds. Finally, the High Contrast Imaging Testbed (HCIT, see section 8.3) is a JPL developed resource for the high-contrast community. It allows investigators to develop, test and validate the key technologies needed by the Terrestrial Planet Finder Mission. HCIT has already achieved wavefront error levels that exceed the ExAOC requirements. JPL will be responsible for the development of calibration techniques capable of achieving and maintaining the levels of static wavefront error needed for ExAOC.

J. Kent Wallace is the lead for the TPF Nulling Interferometer effort at the Jet Propulsion Laboratory, and is a leading contributor to wavefront sensor subsystem of the Palomar Adaptive Optics System. He has over a decade of experience in optical fabrication both at JPL and in industry. He will lead the JPL effort and evaluate different wavefront sensing techniques. (16 weeks effort.)

Joseph Green is a Senior Member of the Engineering Staff responsible for the implementation of high contrast wavefront sensing concepts on the High Contrast Imaging Testbed He has also developed and applied wavefront sensing and control techniques for segmented optics systems for the James Webb Space Telescope project. He will simulate and test ExAO wavefront concepts, drawing on his HCIT experience. (15 weeks effort.)

Mitchell Troy is the lead for the Adaptive Optics group at the Jet Propulsion Laboratory. He has over thirteen years of experience in wavefront sensing and control techniques on large astronomical telescopes. (5 weeks effort.)

Stuart Shaklan is a Principal Engineer, the TPF Coronagraph Architect at the Jet Propulsion Laboratory, and a member of the Space Interferometry Mission Science Team. He is also a Co-

Investigator in the Stellar Planet Survey, a part of the NASA Origins Program. He will assist with development of wavefront sensing techniques and evaluation of coronagraph approaches.

B. Martin Levine is the Deputy Leader of the Interferometry Center of Excellence, and the Manager of the Advance Telescopes Technologies and Concepts Office at the Jet Propulsion Laboratory. He has 20 years experience in the design and construction of adaptive optics systems. He will provide management support/oversite for the JPL effort.

Michael Shao is the Project Scientist for the Space Interferometry Mission, and the Keck Interferometer at the Jet Propulsion Laboratory. He has been a major contributor to the development of ground and space interferometry for over 20 years, including the first paper proposing that wavefront control could create a "dark hole" region. He will provide advice and guidance on the merits of candidate calibration techniques, and will participate in the evaluations of the proposed methods.

7.8 UCLA

The UCLA infrared laboratory has constructed several state of the art infrared instruments since its founding in 1989, including the "Gemini" dual-beam IR camera for Lick Observatory and the NIRSPEC spectrometer for Keck. UCLA also played a major role in the NIRC2 Keck AO camera. Currently under construction is the OSIRIS integral field spectrometer, which will commission at Keck this year. UCLA will be responsible for studying an integral field unit for ExAOC, as well as helping to evaluate infrared detectors.

James Larkin is an Associate Professor of Physics and Astronomy at UCLA. He is a founding member of the NSF Center for Adaptive Optics and served for two years as the associate director for Astronomical Instrumentation within the center. Professor Larkin was also a member of the science team for the TRW portion of the Terrestrial Planet Finder preliminary architecture study and produced detailed simulations of interferometer performance. He has also served on the NASA ORIGINS subcommittee for the past 3 years. Professor Larkin is the PI of OSIRIS, and has been a co-I or PI of the three previous AO instruments at Keck. He is principally responsible for the IFU instrument design and will assist with instrument trade studies. (9 weeks effort.)

Ian McLean received his PhD from Glasgow University in 1974. He joined the faculty at UCLA in 1989 where he is now Director of the Infrared Lab. His research interests include infrared spectroscopy of brown dwarfs and he has led many optical/infrared instrument projects over the past 30 years. Most recently he was PI for the Keck NIRSPEC instrument from 1994-1999 and is currently PI of FLITECAM, a near-infrared camera for SOFIA. In addition to over 250 published papers, he is the author of two books on astronomical instrumentation. Prof. McLean also serves as co-chair of the Keck Science Steering Committee and an Associate Director of UCO/Lick Observatory. He will play a management support role for UCLA, assist in developing instrument designs and performing trade studies, and would track the development of new high-speed IR array detectors which may be useful as wavefront sensors. (4 weeks effort.)

7.9 Other Institutions

Boston Micromachines is the world's leading manufacturer of MEMS deformable mirrors. Paul Bierden and Tom Bifano of BM will collaborate with us on testing their 1024-actuator continuous-facesheet MEMS mirrors in the ExAO testbed, and on the design of a 4096-actuator MEMS suitable for ExAOC.

James Lloyd is a Milliken fellow at the California Institute of Technology and an expert in AO instrumentation, coronagraphy, and interferometry. He will work on both the coronagraph and calibration teams, providing a crucial connection between these two subsystems. (5 weeks effort.)

7.10 Science team

James Graham, the project scientist, has formed a team of astronomers including world-class experts in several ExAO science fields, such as Geoff Marcy, co-discoverer of the majority of known extrasolar planets. The science team will work to ensure that the system performance requirements are driven by the most important science questions, so that the ExAOC system is ultimately capable of producing results of broad scientific significance.

James Graham is Project Scientist and a Professor of Astronomy at the University of California at Berkeley. He was project scientist for the Keck/NIRSPEC spectrometer and PI for the Lick IRCAL polarimeter/AO camera. He will coordinate science team activities, refine Monte Carlo trade-study tools, and develop and maintain traceability of science requirements. (8 weeks effort.)

Eugene Chiang is an Assistant Professor in the Departments of Astronomy and Earth and Planetary Sciences at the University of California at Berkeley. He is a expert in dynamics of planetary systems and circumstellar disks. He will devise observational tests of planet formation via core accretion vs. gravitational collapse and explore how structure is imprinted on ExAOC-detected disks.

Doug Johnstone is an Astronomer at the Herzberg Institute of Astrophysics/National Research Council of Canada. He works on the formation of young stars and the evolution of protostellar disks. He is Project Scientist for ALMA Band 3 (100 GHz) Receiver and a JWST NIRCam Science Team Member. He will explore how structure is imprinted on ExAOC-detected disks, including planetary and non-planetary signatures.

Paul Kalas is a Research Astronomer at the University of California, Berkeley. He is an expert in is coronagraphy and debris disks. He recently discovered the AU Microscopii debris disk. He will construct a tool kit for simulating images of debris disk including polarization. He will develop and simulate methodology for optical detection of disks in ExAOC data and construct the catalog of target stars for debris disk imaging.

Franck Marchis is a Research Astronomer Research Astronomer at the University of California, Berkeley. His research interests include binary asteroids, vulcanism on Io, and deconvolution techniques. He will develop the case for solar system science: high contrast imaging of icy moons, vulcanism, asteroids, Uranus & Neptune.

Geoff Marcy is a Professor of Astronomy at the University of California, Berkeley. His research is focused on the detection of extrasolar planets and brown dwarfs. His team has discovered several dozen extrasolar planets, allowing study of their masses, radii, and orbits. He is Director of Berkeley's Center for Integrative Planetary Science, designed to study the formation, geophysics, chemistry and evolution of planets. He will develop methods and algorithms for measurement of orbital elements. Explore synergy of direct imaging and Doppler searches.

Jenny Patience is a Michelson Fellow in the Astronomy Department, California Institute of Technology. Her research includes work on high angular resolution studies of binary stars and star formation, large-scale stellar and substellar companion searches. She will construct catalogs of open clusters in the solar neighborhood for targeted searches and explore what ExAOC can learn about the properties of binary stars.

Inseok Song is an Assistant Astronomer at UCLA. He has been leading a project to find the youngest, closest stars to Earth during the past few years. Including the nearest young stellar group, beta Pictoris moving group, ~300 young nearby stars have been identified to date. He will construct catalogs of young associations and moving groups in the solar neighborhood for targeted searches and summarize techniques and tools for evaluating the age of the field population.

Yanqin Wu is an Assistant Professor in the Department of Astronomy & Astrophysics, University of Toronto. Her recent work has focused on planet migration, planetary interiors structure and atmospheric dynamics. She is also an expert on the structure of debris disk & proto-planetary disks. She will explore how planetary signatures are imprinted on ExAOC detected disks

In addition, Rene Doyon, and Ben Oppenheimer, and Bruce Macintosh will serve on the science team.

8 Resources and facilities

8.1 UCSC Laboratory for Adaptive Optics ExAO testbed

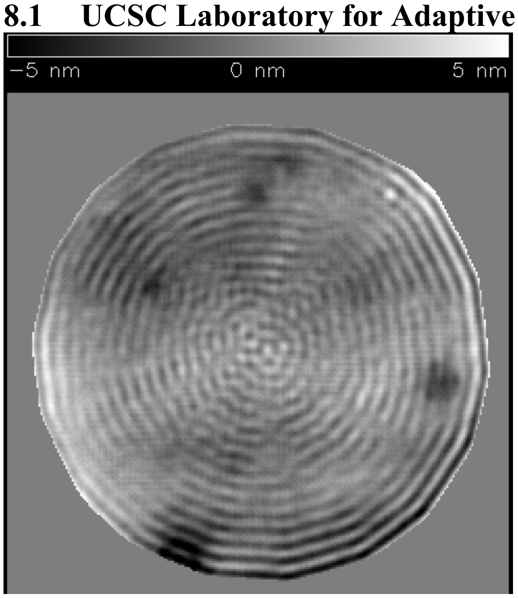


Figure 15: Measured wavefront of the first-generation testbed with a flat mirror. The RMS wavefront error is <1.3 nm. The ringing is caused by diffraction off the focal-plane aperture and is <0.3 nm in RMS amplitude.

Funding from a $9.1M grant to UCSC from the Gordon and Betty Moore foundation has been used to develop the Laboratory for Adaptive Optics. One of the two primary missions of this laboratory is to develop planet-finding extreme AO systems. Currently we are constructing a ExAO testbed in the Laboratory to verify key components and concepts in AO.

The approach we have taken is to build up a testbed from simplicity to complexity, beginning with extremely high quality optical components and adding complex optics and aberration sources as we develop. The first phase of the testbed consists of a high-quality lens (rms ~1-2 nm over 10-20 mm pupil), a MEMS mirror, and a point source reimaged onto a detector. The contrast of such a system will be limited only by our ability to control the MEMS itself. The system does not contain a Lyot coronagraph, which would add additional optics; instead we suppress diffraction though shaped pupil masks (Kasdin et al. 2003).

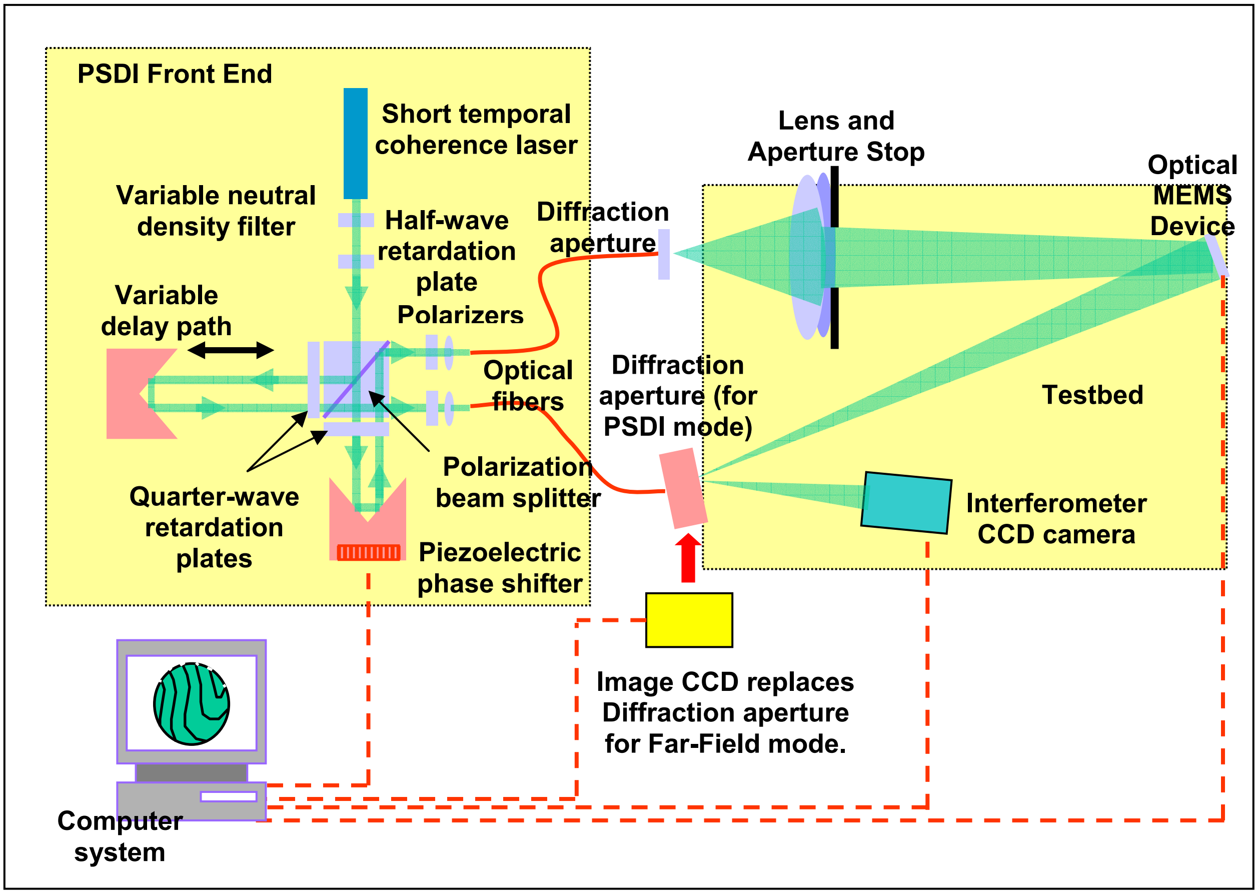


Figure 16: Layout of the PSDI and ExAO testbed.

8.2 UCO shops and facilities

The UCO/Lick Observatory Technical facilities' machine shop has common conventional machining capability as well as CNC milling and turning. The shop is capable of taking CAD files from the engineering group and produce hardware using Surfcam Computer Aided Machining. The machine shop produces and dresses all the optical shop tooling used in plunge-grinding the complex aspheric surfaces generated in the Lick Optical Lab. The Optical Fabrication Lab can test spherical surfaces interferometrically using a Zygo interferometer equipped with a F/1.5 Transmission Sphere affording full surface coverage. Aspheric surfaces can be measured and qualified on the Lick profilometer, used for in-process and final qualification of axi-symmetrical aspherical surfaces. The profilometer has been the proven buy-off test for all of the aspherical surfaces made at Lick, including the secondary mirrors for the Keck I and Keck II telescopes. This is an opto-mechanical measuring instrument built on a seismically isolated granite table base. Sub-nm metrology can be provided by the PSDI in the LAO described above. The engineering department is group of talented engineers skilled in Autodesk Inventor and ANSYS for thermal and structural and dynamic analysis. The Electronics Lab designs and constructs electronic and electro-mechanical devices for new astronomical instrumentation at the Lick and Keck telescopes. There is also an Optical Coatings Lab that can coat and test optics on-site.

8.3 JPL High-contrast imaging testbed

The high contrast imaging testbed (HCIT) at JPL was constructed for developing, testing and validating the key technologies needed by the Terrestrial Planet Finder Mission – whose requirements are even more severe than ExAOC. The testbed consists of a wavefront control system, a coronagraph, and a re-imaging system. The wavefront control system is currently configured with a single Xinetics 32x32 actuator deformable mirror. The current coronagraph employs an array of transmissive occulting spots, which are all written on a common high electron beam sensitive glass substrate, as well as an array of hard-edged Lyot stops. After the coronagraph, the reimaging system presents a magnified far-field pattern to the science camera for scoring the contrast performance of HCIT. This testbed has proven to be an excellent platform for demonstrating DM and occulting spot technologies as well as a facility to develop and establish several wavefront sensing and control strategies. The stability of the environment combined with the fine controllability of its DM, has enabled HCIT to achieve better that 10^{-8} contrast, which is a floor consistent with the noise in the DM drive electronics. We will have access to the HCIT to verify calibration algorithms, and access to test data on the Xinetics DMs and coronagraph concepts.

8.4 The Lyot project coronagraph and AMNH laboratory facilities

The new Astrophysics Laboratory at the American Museum of Natural History includes a class 10,000 clean room, and advanced optical testing equipment including a Zygo GPI-xHr interferometer capable of sub-nm wavefront measurements. The lab is about to acquire a coordinate measuring machine, increasingly needed for complex optical system assembly and alignment. The Laboratory's first instrument, The Lyot Project coronagraph, was built with an end-to-end wavefront error of 30 nm RMS, including the effects of 8 optical surfaces. The Lyot Project coronagraph will be used to validate the various coronagraph options described in this proposal by testing them on a real coronagraph at a real observatory. This will provide perhaps the most crucial information in the down-select from options to final design choice for the Gemini ExAOC.

9 Budget discussion and cost sharing

Table 2 summarizes the budget for the project. The costs have been developed using the detailed work breakdown structure (WBS) shown in Appendix E.

Table 3: Budget summary

Task And Institution	External Funding					Direct Gemini Funding	TOTALS
	In-kind	CfAO & LLNL	LAO	HIA	INO		
Management, Error Budget, AO, Algs, SW (LLNL)		$210,902	$81,340				**$292,242**
Science Case (UCB, et. al.)	$42,210						**$42,210**
Sys Eng, Algs, SW (HIA)	$30,735			$64,625		$100,274	**$195,633**
Opto-Mech, SW (UCO/Lick)			$86,882				**$86,882**
Calibration (JPL)	$9,432	$143,360					**$152,792**
Coronagraph (AMNH)	$24,459						**$24,459**
Coronagraph (STSci)	$19,099	$41,876					**$60,975**
Integral Field Unit preliminary (UCLA)	$31,325					$17,350	**$48,855**
Multi-WL Imager preliminary (INO)					$56,188	$26,675	**$82,863**
Multi-WL Imager preliminary (UdeM)	$56,200						**$56,200**
Post-downselect science instrument design						$29,165	**$29,165**
Travel		$23,890	$3,090			$14,166	**$41,146**
UCSC subcontract charge						$12,250	**$12,250**
4k MEMS development contract			$17,220				**$17,220**
TOTALS	**$213,460**	**$420,028**	**$188,532**	**$64,625**	**$56,188**	**$199,880**	**$1,142,712**

As a result of the external funding, the direct Gemini funding for this project can be focused at the institutions where it is most needed: the Canadian partnership, and development of the science instrument, which is not included in the current CfAO ExAO work. Additional details on which tasks are support by which sources of funding are given in the Project Plan Section (4), and further details are shown in the WBS (Appendix E.)

Funding has been allocated at both UCLA and UdM/INO for the initial analysis of both an MCDA and an IFU science instrument concept, as discussed in section 5.7. After one or the other concept has been selected, a further $29,000 will be allocated between the two institutions to refine the design of the selected instrument. Since UCSC contract rules prohibit carrying such a contingency in the official budget, the formal budget forms show the scenario in which the entire subcontract goes to UCLA. The WBS shows effort for both contingencies.

10 Appendix A: Scientific rationale for ExAOC

10.1 Architecture of Planetary Systems

As of this writing 110 extrasolar planets are listed by Marcy (2004) and 5% of targeted stars possess massive planets. Doppler surveys show that a variety of exoplanet systems exist, but they leave long-standing questions about planetary systems unanswered: How do planets form? Is the solar system typical? What is the abundance of solar systems? Doppler surveys also raise a host of new questions including: What produces the dynamical diversity in exoplanet systems? Direct imaging can answer these questions by offering a fast alternative to Doppler surveys for searching the greatest stellocentric distances for planets. Characterizing the frequency and orbital geometries of planets beyond 3 AU will finally enable us to answer whether orbital configurations like our own planetary system are commonplace, reveal the zone where planets may form by direct gravitational instability, and uncover traces of planetary migration.

The abundance of circumstellar disks might lead one to suspect that frequency of planetary systems may be as high as 15 to 50%: a range that is defined by the occurrence of debris disks and protostellar disks. The low detection rate of planets may be a consequence of the biases inherent to search methods that detect orbital motion. For a reliable detection a significant fraction of an orbital period must elapse. For example, in the Keck radial velocity search, that began in 1996 July, only planets with $a < 3.7$ AU have completed one orbit (Butler et al. 2003). The median semimajor axis of known exoplanet orbits is 0.9 AU and only one planet has a > 5 AU (55 Cnc d at 5.9 AU). The sample of exoplanets appears to be incomplete for a > 3 AU and the underlying distribution of planets in log(a) is at least flat (Stepinski & Black 2001) if not rising (Tabachnik & Tremaine 2002; Lineweaver & Grether 2003). Thus, a direct-imaging search of outer solar system regions (4-40 AU) would increase the total number of planets found relative to those in inner solar system orbits (0.4-4 AU). For a surface density law that meets the requirements of the minimum solar nebula ($\Sigma \sim r^{-3/2}$) such a search would approximately quadruple the total number of known planets. Enlarging the sample of known extrasolar planets is a worthy goal and a primary reason to develop alternative discovery methods.

A second and fundamental motivation to image the outer regions of solar systems is to sample the regions where Jovian planets are thought to form and quantify the greatest distance out to which giant planets can form. The location of the region of interest depends on at least two competing factors: time-scales for planet building and the availability of raw material. Dynamical and viscous time scales in the disk are shorter at small radii, while for typical mass surface density laws the amount of mass increases with radius, with a jump in the abundance of solid material beyond the "snow line" where ices condense. The change in the surface density of solid material occurs at 2.7 AU in the Hayashi model (Hayashi 1981). The location of this boundary depends on the disk structure (Sasselov & Lecar 2000) but for solar type stars the zone of interest is beyond that which is readily probed by the Doppler method. The discovery of giant planets far beyond the snow line would lend support to theories of planet formation by gravitational instability rather than by solid core condensation. At larger orbital radii (> 30 AU) gas cooling times become shorter than shearing time---a necessary condition for runaway gravitational instability (Gammie 2001; Johnson & Gammie 2003; Boss 2002)---while solid core growth by collisional coagulation of planetesimals proceeds prohibitively slowly (Goldreich, Lithwick, & Sari 2004).

A third reason to image the outer regions of extrasolar systems is to probe them for vestiges of planetary migration. Ninety percent of the Doppler sample consists of planets with $a < 3$ AU, suggesting that they represent planets that have migrated inwards to their present locations. A variety of mechanisms may drive orbital evolution; the tidal gravitational interaction between the planet and a viscous disk (Goldreich & Tremaine 1979, 1980), the gravitational interaction between two or more Jupiter mass planets (Rasio & Ford 1996), and the interaction between a planet and a planetesimal disk (Murray et al. 1998). It is energetically favorable for a Keplerian disk to evolve by transporting mass inward and angular momentum outward (Lynden-Bell & Pringle 1974). Inward planetary drift appears inevitable, and this is what is found in certain simulations (Trilling, et al. 2002; Armitage et al. 2002). However, if planets form while the disk is being dispersed, or if multiple planets are present, outward migration can also occur. In a system consisting initially of two Jupiter-like planets a dynamical instability may eject one planet while the other is left in a tight, eccentric orbit. The second planet is not always lost. The observed Doppler exoplanet eccentricity distribution can be reproduced if the 51 Pegasi systems are formed by planet-planet scattering events and the second planet typically remains bound in a wide ($a > 20$ AU), eccentric orbit (Rasio and Ford 1996; Marzari & Weidenschilling 2002). Divergent migration of pairs of Jupiter-mass planets within viscous disks leads to mutual resonance crossings and excitation of orbital eccentricities such that the resultant ellipticities are inversely correlated with planet masses (Chiang, Fischer, & Thommes 2002). Given decreasing disk viscosity with radius and the consequent reduction in planetary mobility with radius, we expect eccentricities to decrease with radius, perhaps sharply if the magneto-rotational instability is invoked (Sano et al. 2000). By contrast, excitation of eccentricity by disk-planet interactions requires no additional planet to explain the ellipticities of currently known solitary planets (Goldreich & Sari 2003). Clearly, observations of the incidence, mass, and eccentricity distributions of multiple planet systems would sharpen our nebulous ideas regarding how planetary orbits are sculpted.

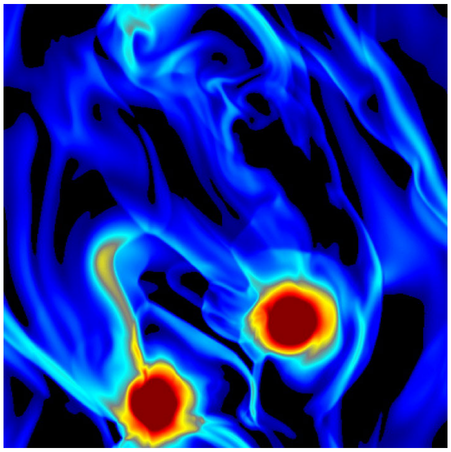


Figure 17: At greater stellocentric distances, planet formation may proceed by gravitational instability of gas rather than by condensation of a seed rocky core. Direct imaging of the outer regions (10-30 AU) of solar systems may detect gas giants formed via this first channel. This image from Gammie (2001) displays two clumps of gas undergoing runaway gravitational collapse in a circumstellar disk; colors trace disk surface density. At later times, the two clumps collide and merge to form a self-gravitating protoplanet.

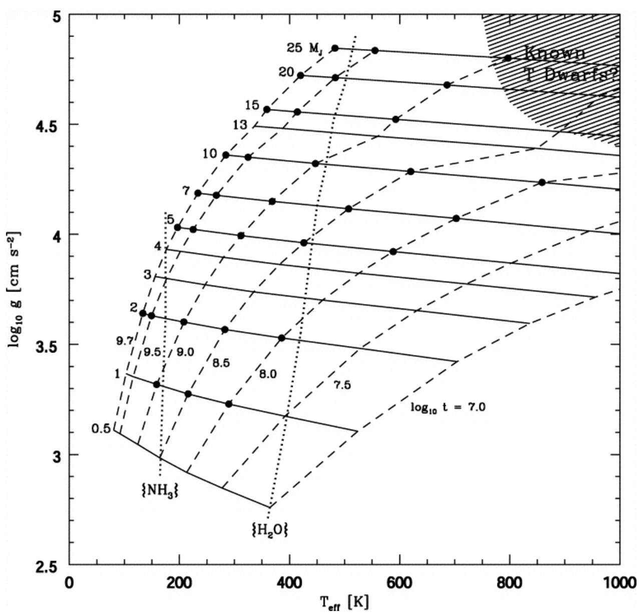
Imaging also provides a snapshot with the potential to reveal multiple planets, zodiacal dust structures, and brown dwarves or stellar companions. By comparison, the Fourier method implicit in indirect searches requires the completion of multiple orbits to disentangle complex systems. The presence of stellar and/or brown dwarf companions and their potential dynamical influence on neighboring planets can be revealed immediately (cf. the case of HD 80606b studied by Wu & Murray (2003)). In the absence of transits, astrometric measurements of the motion of the primary, or direct detection the orbital inclination and hence the mass of the planet is unknown to a factor of sin i. Furthermore, direct detection can access a wider variety of host stars than current Doppler techniques, including higher-mass A and F stars having weak photospheric absorption lines, and pre-main-sequence stars whose chromospheric activity introduces kinematic jitter. Detection of planets orbiting young stars is practical because of the high luminosity of freshly assembled planets, but would provide direct constraints on timescales for planet formation.

10.2 Planetary Atmospheres

To understand why direct detection of luminous, young planets is feasible, we must first consider their atmospheres. With the exception of rare transiting planets, e.g., HD 209458, we have no observations of the atmospheres of exoplanets, and we must be guided by observations of cooler and hotter objects, and by theory.

The discovery of Gliese 229B (Nakajima et al. 1995; Oppenheimer et al. 1995) and the 2MASS (Reid 1994), Sloan (Strauss et al. 1999) and DENIS (Delfosse et al. 1997) surveys have launched a new era in stellar astronomy. The L and T dwarfs (Kirkpatrick et al. 1999, 2000; Burgasser et al. 1999, 2000a, 2000b, 2000c) are the first fundamental spectroscopic classes to be added to the stellar alphabet in nearly a century. The L dwarfs delineate the lower edge of the solar-metallicity main sequence, with effective temperature near 1700 K. More than 200 L dwarfs with T_{eff} = 2200-1300 K are now known. The coolest L dwarfs are brown dwarfs, objects with insufficient mass (< 0.074 $M_{\odot}$) to burn H on the main sequence (Burrows et al. 2001). About 40 T dwarfs have been cataloged, spanning the T_{eff} range from 1200 to 750 K. These are all brown dwarfs.

Figure 18 from Burrows et al. (2003) Gravity vs. T_{eff} for a range of brown dwarf masses (0.5-25 M_J) and ages (0.01-5 Gyr). Solid curves are evolutionary tracks, dashed curves are isochrones. Condensation curves for H_2O and NH_3 are plotted as dotted lines. For objects to the left of these lines, the corresponding condensate will form in the atmosphere. H_2O is expected to condense in the atmospheres of a sizable subset of these objects, while NH_3 is expected to condense for only the lowest mass, oldest objects. The hatched region in the upper right shows currently known T dwarfs. They occupy only a small fraction of the depicted phase space.



While there have been claims of the discovery of free-floating planetary mass (< 13 M_J) objects (Zapatero Osorio et al. 2000), the edge of the mass function, either in the field or in star clusters has not yet been reached (McGovern et al. 2004). A wide gap in T_{eff} (150 K < T_{eff} < 800 K) exists between the currently known T dwarfs and cool, solar Jovian planets (see Figure 18). However, these objects must exist as the youthful progenitors of the known population of Doppler-detected exoplanets. Figure 19 shows spectra of a 5 M_J exoplanet as a function of age showing the distinctive peaks due to enhanced flux between the water vapor absorption bands (0.93, 1.1, 1.4, 1.8 & 6.5 μm). Thus, the ground-based near-IR *JHK* bands, which are defined by the same H_2O opacity are ideal bands at which to seek a detection.

Detection and spectroscopy of the light from planets opens their atmospheres to the study of temperatures, gravities and compositions. These objects represent planetary *terra incognita*. For example, at T_{eff} below 400-500 K water condenses in planetary atmospheres. The appearance of water ice clouds constitutes a significant milestone along the path from the known T dwarfs to the giant planets. Associated with cloud formation is the depletion of water vapor above the tops of the water cloud. Within 100 Myr, water clouds form in the atmosphere of an isolated 1 M_J object. The presence of clouds of any sort emphasizes the kinship of this transitional class with solar system planets, in which clouds play a prominent role. On Jupiter itself water clouds are too deep below the ammonia cloud layer to have yet been unambiguously detected.

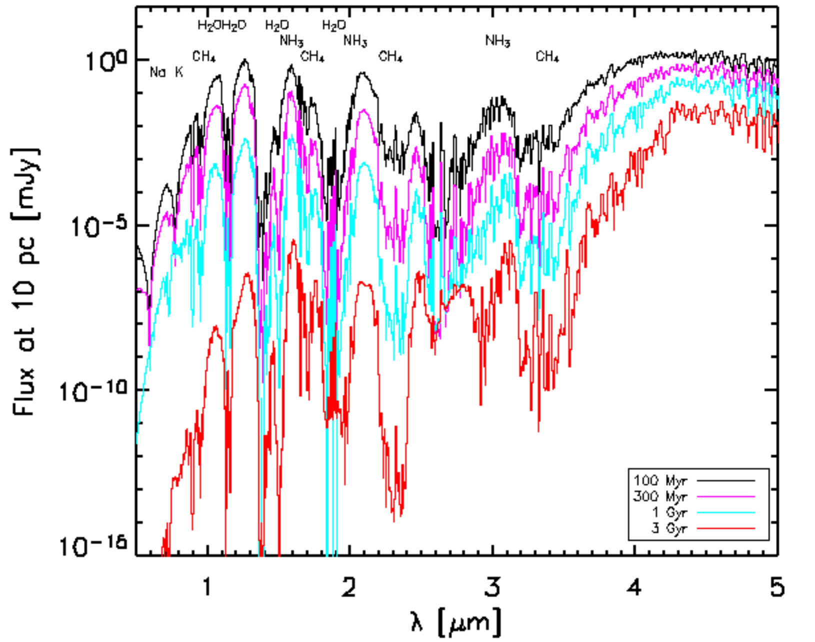


Figure 19: Spectra of a 5 M_J exoplanet as a function of age showing the distinctive peaks due to enhanced flux between the water vapor absorption bands (0.93, 1.1, 1.4, 1.8 & 6.5 μm) typical of brown dwarfs. Other general features are the broad hump at 4.5 μm, CH_4 features at 1.7, 2.2, & 3.3 and the NH_3 features at 1.5, 1.95, & 2.95 μm. The strengths of each of these features are functions of mass and age.

10.3 Scattered light imaging of debris disks

Debris disks are the extrasolar analogs of our Zodiacal dust disk (<3 AU) and the dust complex generated in the Kuiper Belt (40-50 AU; Ladgraf et al. 2002). They are optically thin and gas-poor. Debris disks arise from the collisional erosion of larger solid objects, but may include a contribution from subliming icy bodies as they pass through periastron. Key motivations to study these disks are the following:

- Unlike hot Jupiters, a handful of debris disks are spatially resolved in scattered light by current instrumentation and these systems present an early observational test for ExAOC, and an opportunity to refine observing and data reduction procedures

- Dust optical depth and age are correlated (Spangler et al. 2001). Thus, stars with the dustiest debris disks are among the youngest stars in the solar neighborhood, and some of the best candidates for finding self-luminous planets.

- Debris disk morphology gives several constraints on where to look for planetary bodies around a star, including: position angle, inclination of the system to the line of sight, and the radius of a central dust-depleted region approximating the outer radius of the planetary system (e.g., Roques et al. 1994).

- Planet orbital parameters are further constrained by interpreting radial and azimuthal asymmetries in debris disks as the dynamical effects of planet-mass objects (Liou and Zook 1999). For example, the orbital eccentricity of a detected planet may be constrained by disk structure before the actual orbit is observed in multi-epoch data.

- For older stars in the sample, where self-luminous objects are dim, the analysis of debris disks still characterizes the possible, unseen planetary system, perhaps leading to follow-up observations with future facilities such as Terrestrial Planet Finder. The debris disk analysis may include multi-epoch observations that show the rotation of disk features, that can then be linked to the mass and location of planetary objects (Ozernoy et al. 2000).

How sensitive is our straw man ExAOC design to debris disks? To answer this question we adopt as a benchmark the currently most observationally challenging debris disk - HR 4796A. Thermal infrared fluxes indicate a dust optical depth $L_{dust} / L_{bol} = 5 \times 10^{-3}$ (Jura 1991), with the dust confined to a ring 1" radius (67 AU) from the star (Schneider et al. 1999). Using the *H*-band flux densities, the contrast relative to the central star, and the disk inclination (i = 73˚) measured in HST NICMOS images we generate a disk model that matches the observed flux densities. We also produce models that present the ring at different viewing geometries, and insert these model disks into model ExAOC PSFs representing a 10 sec integration on Gemini. Figure 5 in section 2.5shows the results. A key result is that HR 4796A dust ring is easily detected by EXAOC because of the depth of the null surrounding the central PSF core.

The fundamental result is that debris disks with 1/10 th the scattered light of HR 4796A are rapidly detectable at any inclination out to ~ 70 pc. A debris disks with 1/100 th the scattered light of HR 4796A is detectable for most inclinations. The disk signal is extracted by employing PSF subtraction. During the conceptual study phase we will elaborate methods to measure the PSF and quantify its stability. Our goal is to enable the detection of a disk with 1/100th the dust optical depth of HR 4796A ($\tau \sim 5 \times 10^{-5}$) at any inclination. IRAS data shows that ~15% of all stars have IR excess due to dust at this level (Backman & Paresce 1993) and hence all of these will be detectable.

10.4 Solar System Exploration with ExAOC

Over the last thirty years, planetary science has been revolutionized by the development of spacecraft that permit high angular resolution observations. Recently, large, ground-based telescopes equipped with adaptive optics systems have become competitive with remote sensing platforms and bring new information about the nature, origin, and possible geological activity of the bodies orbiting around our Sun.

High contrast imaging with ExAOC has the potential to: a) Characterize the surface and atmospheric composition of Galilean satellites and Titan, and monitor the volcanic activity of Io; b) Determine size, shape, surface morphology of the 50 largest main-belt asteroids, search for extremely faint satellites, and derive direct information about the density and the formation of this remnant of the solar system formation; c) Monitor the atmospheric activity of Uranus and Neptune, focusing especially on the cloud formation and wind profile above the stratospheric haze near the southern pole of Uranus, which is now being exposed to sunlight. Study of Neptune's atmosphere yield information about the transport of energy and the source of its mysterious internal source of heat.

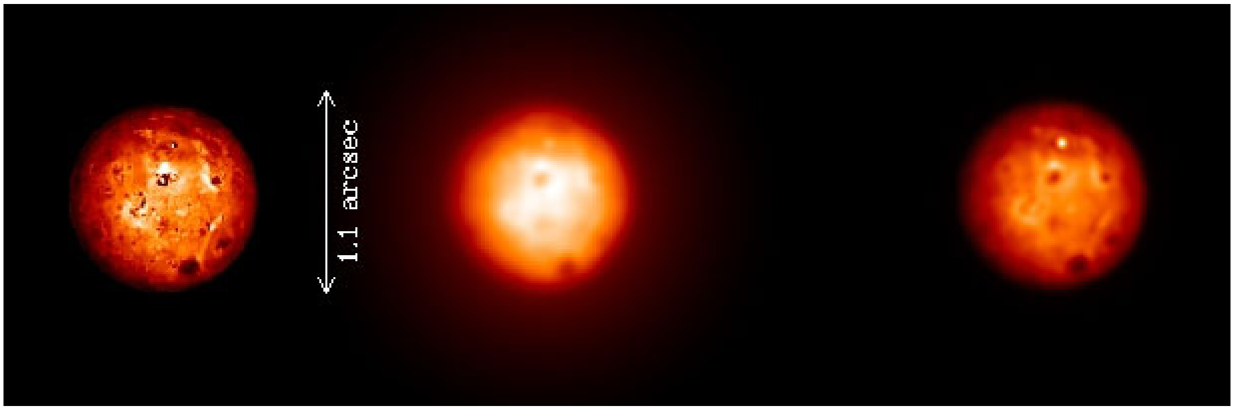


Figure 20-Simulated *H* band ExAOC observations of Io with Gemini. The left panel shows the simulated input image of Io as it would appear observed from the ground at an angular resolution of ~ 10 mas in the absence of the atmosphere (spatial resolution of ~ 30 km at opposition). Surface albedo features such as pateras, plume deposits and SO_2 frost regions are dominant on this image. The center and right panels show the results of the simulation of observations with Altair-NIRI (center) and ExAOC (right). The input image was convolved with a real GEMINI/NIRI PSF. The gain in contrast and angular resolution is evident. An artificial faint hot spot located close to the north pole of Io is detectable only in the ExAOC data. Detection of the thermal emission of hot spots in J and H bands is normally possible only during eclipses, during which AO observations of Io are extremely difficult.

10.5 Targeted Planet Searches in Open Clusters and Young Associations

Although a field survey of the solar neighborhood is a primary objectives of ExAOC, targeted searches, such as in young clusters will yield core science regarding the formation and evolution of planetary systems. As products of a single star formation event, open clusters represent ideal targets samples with known ages, distances, and metallicities. Within a cluster, it is possible to conduct planet searches that eliminate uncertainties about different environmental factors. Combining all the open cluster targets provides a large sample of youthful stars (ages 90-660 Myr) that formed in regions of high stellar density. The young ages of open clusters enhance the planet detection threshold since young giant planets are more luminous, and the nearby distances ensure that separations comparable to the sizes of the solar system and circumstellar disks are resolvable.

A plot of the ages and distances of the nearest open clusters is given in. The closest clusters are visible in the Northern Hemisphere, while the youngest clusters are located in the Southern Hemisphere.

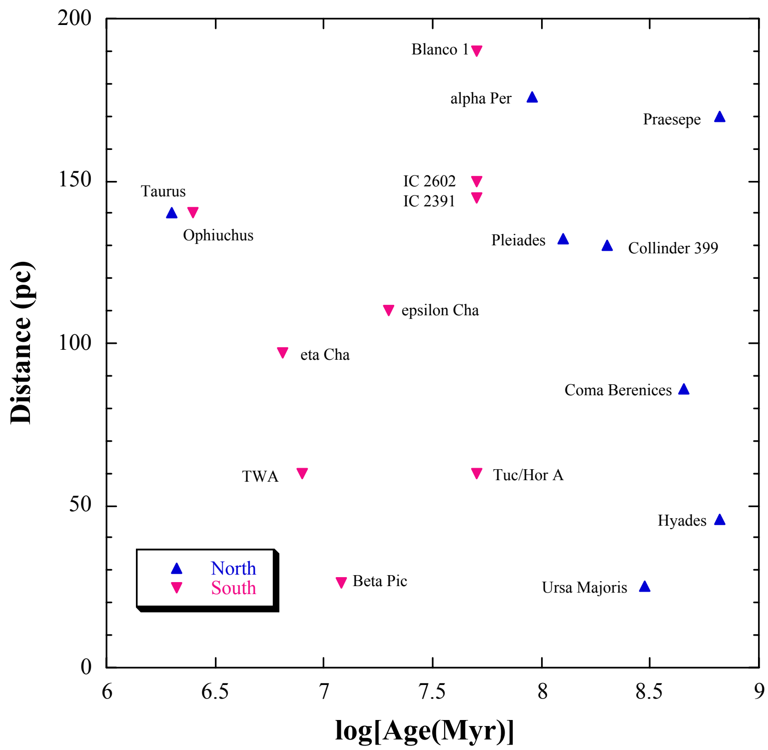


Figure 21: Nearby open clusters, associations, and star-forming regions

Ursa Majoris and Coma Berenices are sparsely populated, while the Hyades, Pleiades, and α Persei have substantial membership. Most clusters are out of the Galactic plane and the closest have high proper motions, allowing confirmation of true companions within a year. The total number of open cluster members satisfying the magnitude limit (R < 8mag) is substantial, 233 stars; this large sample is critical given the limited frequency of extrasolar planets detected by large scale radial velocity searches. For the closest clusters, both early-type and solar-type stars are feasible targets, however, only early-type stars are bright enough in the Pleiades and alpha α Persei.

Until the late 1990s only two nearby (< 100 pc), coeval, comoving groups of stars were known: the rich Hyades and the sparse Ursa Majoris clusters. Both are hundreds of millions of years old. Then, beginning in the late 1990s, three more stellar groups---the TW Hydrae Association, the Tucana/Horologium Association, and the beta Pictoris Moving Group---were identified within ~100pc of Earth. Recently, two more such groups are identified in addition to the eta Chamaeleontis cluster at 97pc. To date, including all members of nearby young stellar groups plus young nearby stars apparently not belonging to any known groups, about 300 young (8-50 Myr), nearby (< 100 pc) stars are known. These young nearby stars are excellent targets for direct imaging detection of cooling giant planets because of their extreme youth and proximity to Earth. They will also enable imaging studies of the planetary debris disks and early evolution of planetary systems. During the conceptual design phase we will assemble and critically review a catalog of young, nearby candidate stars for a direct imaging survey. Our input list will include one of the most thoroughly vetted samples of young stars, suitable for imaging planetary companions, that of the Spitzer FEPS (Formation and Evolution of Planetary Systems) Legacy Program. Since these represent the ideal targets for a planet search, their properties – magnitude and declination – are major drivers on the design of ExAOC.

11 Appendix B: Physics of high-contrast imaging and error budget

To first order, faint companion searches are prevented by two independent effects: speckle noise from the atmospherically aberrated wavefront, and the diffraction of the telescope and optics on a perfect wavefront. We discuss these two effects separately, although there are solutions which mitigate both effects.

11.1 Residual Speckle Noise and Adaptive Optics

The useful dynamic range of a ground-based image in the diffraction limited regime is usually limited by speckles caused by residual atmospheric phase errors (Racine et al. 1999). Noise in a long exposure image is dominated by the number of speckles present in the image, and their lifetime, rather than the number of photons in the speckles. For this reason, adaptive optics is needed to reduce speckle noise if faint companions to bright stars are to be detected. Techniques to reduce speckle noise by reducing their lifetimes drastically (Angel 1994) have been proved both analytically and numerically to be ineffective (Sivaramakrishnan et al. 2002).
In Sivaramakrishnan et al. (2002); Perrin et al. (2003) we developed a formalism for expanding the PSF to arbitrary order in terms of powers of the Fourier transform (Φ) of the residual zero-mean phase error (ϕ) over an arbitrarily shaped and apodized entrance aperture (*A*, which can include scintillation effects), in order to understand speckle structure better. We summarize this work here.

The aperture illumination function with phase aberrations is $A_{AO} = AA_{\phi} = Ae^{i\phi}$, with a corresponding `amplitude-spread function' (ASF) of $a_{AO} = a * a_{\phi}$ (where $*$ denotes the convolution operation, and changed case indicates the Fourier transform). A_{AO} can be expanded in a convergent series in ϕ for any finite value of the phase: $A_{AO} = A(1 + i\phi - \varphi^2/2 + \ldots)$. The ASF corresponding to this pupil field is its Fourier transform, $a_{AO} = \sum_{k=0}^{\infty} \frac{i^k}{k!}(a *^k \Phi)$ (we introduce use the *n*-fold convolution for compactness: e.g., $f *^3 g \equiv f * g * g * g$). This results in the PSF being expressed as an infinite sum $p_0 + p_1 + p_2 + \ldots$ where the terms up to second order are

$$\begin{aligned} p(\Phi) = {} & aa^* \\ & - i\left[a(a^* * \Phi^*) - a^*(a * \Phi)\right] \\ & + (a * \Phi)(a^* * \Phi^*) \\ & - \frac{1}{2}\left[a(a^* * \Phi^* * \Phi^*) + a^*(a * \Phi * \Phi)\right], \end{aligned} \tag{1-1}$$

with a general term of

$$p_n = i^k \sum_{k=0}^{n} \frac{(-1)^{n-k}}{k!(n-k)!}(a *^k \Phi)(a^* *^{n-k} \Phi^*). \tag{1-2}$$

The zero order term is the perfect PSF aa^*. The first order term (first discussed by Bloemhof et al. (2001)) is antisymmetric, thus being zero at the image center. It is modulated by the size of the ASF, *i.e.*, it is `pinned' to the bright Airy rings.
The second order term p_2 is composed of two separate terms. The first of these, $p_{2,halo} = (a * \Phi)(a^* * \Phi^*)$, is the dominant term in the extended halo, as its fall-off with radial distance from the core of the PSF is set solely by the spatial frequencies present in the phase function ϕ. It is zero at the image center. It is merely the power spectrum of the phase over the aperture. The second of these, $p_{2,Strehl} = -\frac{1}{2}\left[a(a^* * \Phi^* * \Phi^*) + a^*(a * \Phi * \Phi)\right]$, is the first term in

the expansion to decrease the central peak: in fact it reduces to the Maréchal approximation at the image center. It is modulated by the ASF size, thus decays with distance from the image center. Preliminary data from the Lyot project confirm the existence of this symmetric at extreme Strehl ratios when diffraction has been adequately suppressed.

Because p_1 and $p_{2,Strehl}$ exhibit `pinned' behavior, apodizing the aperture decreases their contributions to speckle noise drastically --- for a clear aperture second order effects dominate speckle formation at about 90% Strehl ratios, whereas apodization makes the second-order halo term dominant at Strehls between 80% and 97%, reducing both p_1 and $p_{2,Strehl}$ by an order of magnitude.

Above Strehl ratios of around 97% the first order term dominates speckle structure. Equation (1-2) demonstrates why speckles are always at least as big as the PSF since Φ is always convolved with *A* whenever it appears.

Adaptive optics, and, to a certain extent, pupil apodization, reduce the speckle noise that limits the dynamic range of the imaging. AO acts on the phase ϕ as a high pass filter in spatial frequency space, with an 'AO control radius' $\lambda/2d$ in image space, where *d* is the actuator spacing of the deformable mirror (assuming a matched wavefront sensor)

11.2 Diffractive Photon Noise, Coronagraphy and Apodization

The perfect, unaberrated, PSF, aa^*, depends only on aperture properties. A clear circular aperture PSF possesses diffraction rings that decay with the third power of angular distance from the star. This makes faint companion searches impossible with simple direct imaging simply because of this background's photon noise. By modifying the pupil throughput by apodization (*e.g.*, Aime et al. (2002); Kasdin et al. (2003)), or changing the shape of the pupil boundary (Jacquinot & Roizen-Dossier 1964; Nisenson & Papaliolios 2001), the spillover of an unaberrated PSF can be suppressed in various areas of interest in the image plane.

A perfect coronagraph on such a telescope removes all the diffractive spillover of light from some area of interest in the image plane. A Lyot coronagraph blocks light at a first image plane with a mask that is opaque at its center. This stop has a characteristic size $s\,\lambda/D$ ($s >$ ~4 for clear apertures), it blocks the core and first few Airy rings of unaberrated on-axis starlight. The beam is then relayed to a pupil called the Lyot plane. Those bright Airy rings not blocked by the stop in the image plane appear as power at the edges of the re-imaged pupil in the Lyot plane: this light is concentrated in a band of order D/s wide around the boundary of the re-imaged pupil, where it can be blocked with a Lyot stop that undersizes the aperture (Sivaramakrishnan et al. 2001).

Combining pupil apodization with even smaller image plane occulting stops ($s >$ ~2.5) is potentially possible (Soummer et al. 2003).

11.3 ExAOC strawman error budget

The figure of merit for the error budget of an ExAOC system is not the total RMS wavefront error or Strehl ratio, but the final achievable contrast. This means that we require tools – analytic or simulation –for translating different wavefront error terms into their effects on contrast. Fortunately, the PSF expansion given above provides a natural way to do this. At radii where diffraction is unimportant – where the coronagraph has suppressed the Airy pattern – the average PSF is given by the power spectra of the wavefront errors. Assuming there are n distinct wavefront error sources and all are uncorrelated, the total PSF intensity (normalized to unity) is then given by $P(\theta) = \sum_i^n \sigma_i^2 I_i(\theta)$ where $I_i(\theta) = <|\phi_i(\theta/\lambda)|^2> / \sigma_i^2$ is a the unity-normalized spatial power spectrum of the phase error ϕ_i and σ_i is the magnitude of the corresponding phase error in radians. A phase error of spatial frequency θ/λ in cycles per meter $D\theta/\lambda$ in cycles per pupil will scatter light to an angular radius θ. This leads to a useful insight: in order to detect planets at radii between 0.1 and 1 arscecond at J band, we need to control phase errors between ~3 cycles per pupil and ~30 cycles per pupil. Lower frequency errors will primarily rearrange light under the coronagraph occulting stop (though the details of how light leaks through the coronagraph are complex for different designs) while higher frequencies scatter light to large radii.

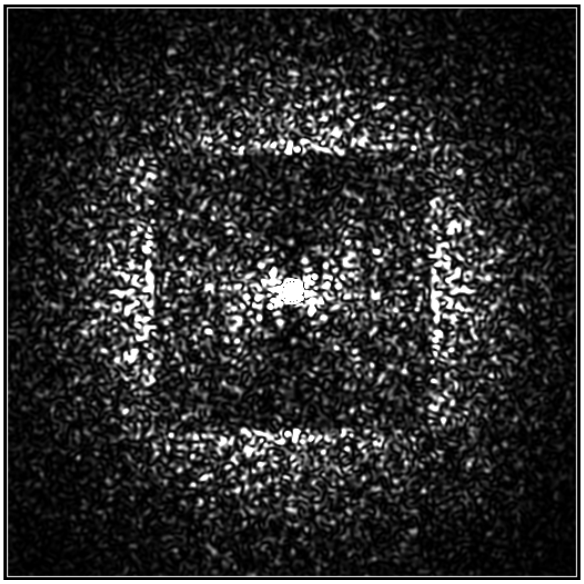


Figure 22: Instantaneous monochromatic PSF showing speckles

Instantaneously, the PSF is completely broken up into speckles (Figure 22) – and these speckles are the main source of noise in an attempt to detect a pointlike object such as a planet. The noise as a function of radius for a single PSF noise source in monochromatic light is given by $\sigma_i^2 I_i(\theta)$ - the noise is roughly equal to the intensity. (In broadband light, an additional term appears decreasing the noise due to the elongation of the speckles; for clarity we will omit this term in this section, though it has been included in our detailed analysis.) Over a long integration, multiple realizations of the speckle pattern will act to smooth the PSF. We express this by assigning each error source a characteristic speckle decorrelation timescale $tdec_i$; in an integration time $t > tdec_i$, the final noise for a single source will be given by $\sigma_i^2 I_i(\theta)\left(\frac{tdec_i}{t}\right)^{1/2}$

If multiple error sources are present, Sivaramakrishnan et al (2002) show that each decorrelates independently, and the total noise in the final image is given by

$$N(\theta,t) = \sum_i^n \sigma_i^2 I_i(\theta)\left(\frac{tdec_i}{t}\right)^{1/2}$$

This means that error sources with rapid decorrelation, such as the random measurement noise of the AO system, are much less significant than errors that decorrelate slowly, such as the atmospheric fitting and bandwidth terms. Errors that do not decorrelate, such as quasi-static optical errors, are the worst of all; as shown by Sivaramakrishnan et al, in an extremely long exposure with both random and static errors, the PSF approaches the noise floor given by the static errors only – the PSF becomes a smooth halo with imprinted on it a speckle pattern equivalent to that given only by the static errors. Figure 23 illustrates this and shows the severe effect of even small static PSF errors.

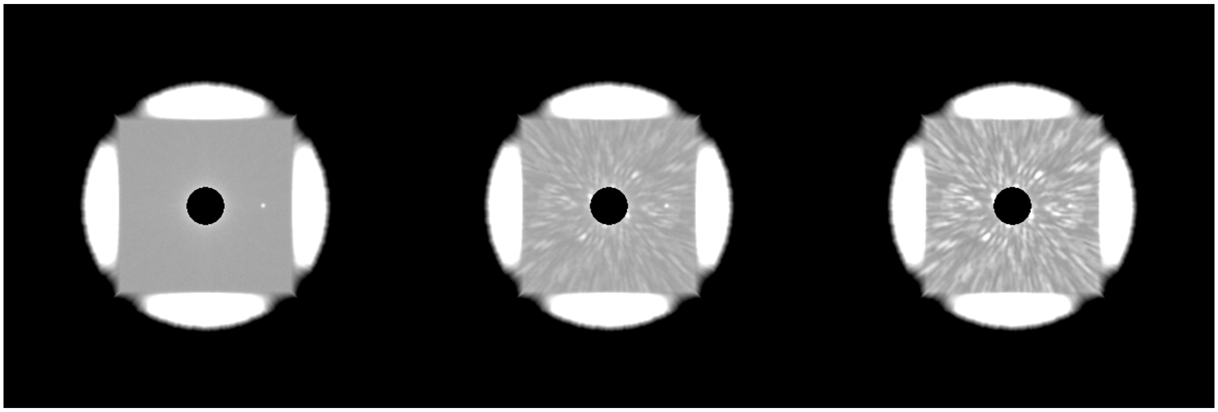


Figure 23 Three simulated 15 minute ExAO images, with 0 (left), 2, and 4 nm RMS random static wavefront error. A simulated planet is located at 3:00.

Table 4 gives an error budget assembled on this basis. We have broken up each error into three spatial frequency ranges: low (<4 cycles/pupil), mid (4 to 31 cycles/pupil) and high (>62 cycles per pupil). We also give the final contribution to the PSF intensity and PSF noise, expressed in terms of contrast relative to the peak intensity of the star, for a 1 hour exposure. A contrast level of $1.5\text{x}10^{7}$ will be reached at the 5-sigma level.

Error term	Low-freq.	Mid-freq.	High-freq.	PSF intensity	PSF noise
Atmosphere	0	2	31	$6.0\text{x}10^{-8}$	$1.0\text{x}10^{-10}$
Telescope	10	0.5	22	$3.8\text{x}10^{-9}$	$4.8\text{x}10^{-10}$
Non-common-path after (before) calibration	5 (20)	1 (10)	10(10)	$1.5\text{x}10^{-8}$	$3.8\text{x}10^{-10}$
Atmospheric bandwidth	16	17	12	$5.4\text{x}10^{-6}$	$9.1\text{x}10^{-9}$
WFS measurement		17		$4.1\text{x}10^{-6}$	$1.4\text{x}10^{-9}$
Uncorrectable internal errors			30	0	0
Quad cell gain changes	0.4	0.2	0	$6.0\text{x}10^{-10}$	$1.5\text{x}10^{-10}$
Flexure	10	1	0	$1.5\text{x}10^{-8}$	$3.8\text{x}10^{-9}$
Total WFE	20	24	51		
Photon noise					$1.8\text{x}10^{-9}$
Total	**59.6 = Strehl of 0.95 at H band**			**$9.6\text{x}10^{-6}$**	**$2.1\text{x}10^{-8}$**

Table 4 Wavefront error budget for the baseline ExAOC system. PSF intensity effects and noise are evaluated at an angle of 0.3 arcseconds. r0=20 cm at 500 nm, wind=20 m/s. Target star m_I=4 m_H=3.4. Observing wavelength 1.5-1.7 microns. Total integration time 3600 seconds. PSF intensity and PSF noise are normalized with respect to the peak intensity of the coronagraphic PSF, so that a PSF noise of $2.1\text{x}10^{-8}$ would represent a 5-sigma detection of a companion with a contrast relative to its primary of $1.5\text{x}10^{-7}$.

Atmosphere: Atmospheric fitting error (which is definitionally high-frequency) and aliasing errors (which are nearly perfectly suppressed by the spatial filter, section 3.1.3.)
Telescope: Residual telescope static and vibrational errors after correction. Placeholder estimate; real Gemini values will be obtained during study from existing Gemini metrology and integrated modeling effort.
Non-common-path: Differential wavefront error between the science camera and the fast wavefront sensor after calibration (section 5.3). Values before calibration are given in parenthesis.
Atmospheric bandwidth: Temporal errors assuming a closed-loop bandwidth of 250 Hz.
WFS measurement: Photon and read noise in the wavefront sensor measurement.

Uncorrectable internal errors: High-frequency internal optical errors.
Quad cell gain changes: Errors due to unmeasured changes in the WFS spot size
Flexure: Changes in the non-common-path errors due to optical flexure.
Photon noise: Total noise in the final image due to Poisson statistics of detected photons in the science camera.

During the design study we will work to refine this error budget and add in additional error terms such as scintillation, chromatic errors, optical reflectivity variations, and dome seeing.

As can be seen in the table, final sensitivity is a factor of ten worse than the photon noise limit, due to speckle noise. If speckle noise can be suppressed through multi-wavelength imaging techniques (section 5.7), one can obtain comparable or higher contrasts while relaxing the static optical requirements. The table below gives an error budget for a ExAOC using a multi-wavelength imager (section 5.7.1).

Error term	Low-freq.	Mid-freq.	High-freq.	PSF intensity	PSF noise
Atmosphere	0	2	31	6.0×10^{-8}	1.0×10^{-11}
Telescope	10	0.5	22	3.8×10^{-9}	4.8×10^{-11}
Non-common-path after (before) calibration	10 (40)	5 (20)	10(10)	3.8×10^{-7}	9.4×10^{-9}
Atmospheric bandwidth	16	17	12	5.4×10^{-6}	9.1×10^{-10}
WFS measurement		17		4.1×10^{-6}	1.4×10^{-10}
Uncorrectable internal errors			30	0	0
Quad cell gain changes	0.4	0.2	0	6.0×10^{-10}	1.5×10^{-11}
Flexure	10	3	0	1.4×10^{-7}	3.4×10^{-9}
Total WFE	21	25	51		
Photon noise					5.8×10^{-9}
Total	**60.4 = Strehl of 0.95 at H band**			**9.6×10^{-6}**	**2.0×10^{-8}**

Table 5 Wavefront error budget for the ExAOC with multiwavelength imager capable of speckle suppression η=10. PSF intensity effects and noise are evaluated at an angle of 0.3 arcseconds. r0=20 cm at 500 nm, wind=20 m/s. Target star m_I=4 m_H=3.4. Total integration time 3600 seconds.

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13 Appendix C: List of acronyms

ADC	Atmospheric dispersion corrector
AMNH	American Museum of Natural History, New York City
AO	Adaptive optics
AOC	Adaptive optics computer – the realtime control computer
ASF	Amplitude Spread Function
ATRG-V	Astronomy Technology Research Group, Victoria
BM	Boston Micromachines
CELT	California Extremely Large Telescope
CfAO	Center for Adaptive Optics, a National Science Foundation Science & Technology Center
CFD	Computational fluid dynamics
CoDR	Conceptual design review
CWFS	Calibration wavefront sensor; the high-precision second wavefront sensor in our ExAOC design
DM	Deformable mirror
EUV	Extreme Ultraviolet
EUVL	Extreme Ultraviolet lithography; a multi-institution project to create technologies for lithography at wavelengths < 100 nm
ExAO	Extreme adaptive optics
ExAOC	Extreme Adaptive Optics Coronagraph, the instrument covered by this proposal
FEA	Finitx10-element analysis
FOV	Field of view
FPRD	Functional and performance and requirements document
FTR	Fourier transform reconsturctor: fourier-based algorithm for reconstructing wavefronts from slope measurements
HCIT	High-Contrast Imaging Testbed: wavefront sensing and control / coronagraph testbed at JPL constructed for support of spacx10-based coronagraph efforts
HIA	Herzberg Institute of Astrophysics
ICD	Interface control document
IFU	Integral field unit
IM	Integrated model
INO	Institut National d'Optique in Quebec, Canada
LAE	Laboratoire d'Astrophysique Expérimentale at the University of Montreal
LAO	Laboratory for Adaptive Optics: a laboratory at UC Santa Cruz dedicated to the development of next-generation adaptive optics, established by a donation from the Gordon and Betty Moore foundation
LGS	Laser Guide Star
LL	Lincoln Laboratories
LLNL	Lawrence Livermore National Laboratory
MCDA	Multi-Color Detector Assembly
MEMS	Micro Electro Mechanical System
MPDA	Multi-Polarization Detector Assembly
MWI	Multi-wavelength imager
OAP	Off-axis parabola
OCDD	Operational concept definition document
PSDI	Phasx10-shifting diffraction interferometer: a sub-nm absolute wavefront measurement system developed by LLNL for EUVL optics characterization

PSF	Point spread function
RTOS	Real-time operating system
SCC	Supervisor/Components control computer
SFWFS	Spatially-filtered wavefront sensor; a fast Shack-Hartmann wavefront sensor with a focal-plane spatial filter to remove aliasing errors
S-H	Shack-Hartmann
SIC	Science instrument computer
SSD	Specklx10-suppressing device
STScI	Space Telescope Science Institute
SW	Software
TMT	Thirty-Meter Telescope
TPF	Terrestrial Planet Finder
UC	University of California
UCB	University of California Berkeley
UCLA	University of California Los Angeles
UCO	University of California Observatories, the organization at UC Santa Cruz responsible for managing UC's observational facilities
UCSC	University of California Santa Cruz
UdeM	Université de Montréal
VLOT	Very Large optical Telescope
VMM	Vector-matrix-multiply algorithm for wavefront reconstruction
WBS	Work breakdown strucutre
WFE	Wavefront error
WFS	Wavefront sensor
XAOPI	eXtreme Adaptive Optics Planet Imager, a CfAO-funded design concept for a ExAO system, designed for the W.M. Keck telescope

14 Appendix D: Contract terms

UCSC has reviewed the proposed contract included as schedule B to the proposed RFP. According to the policy of the University of California Regents, we request that you change the "Choice of Law" clause and replace "Arizona" with "California". No other changes are requested.

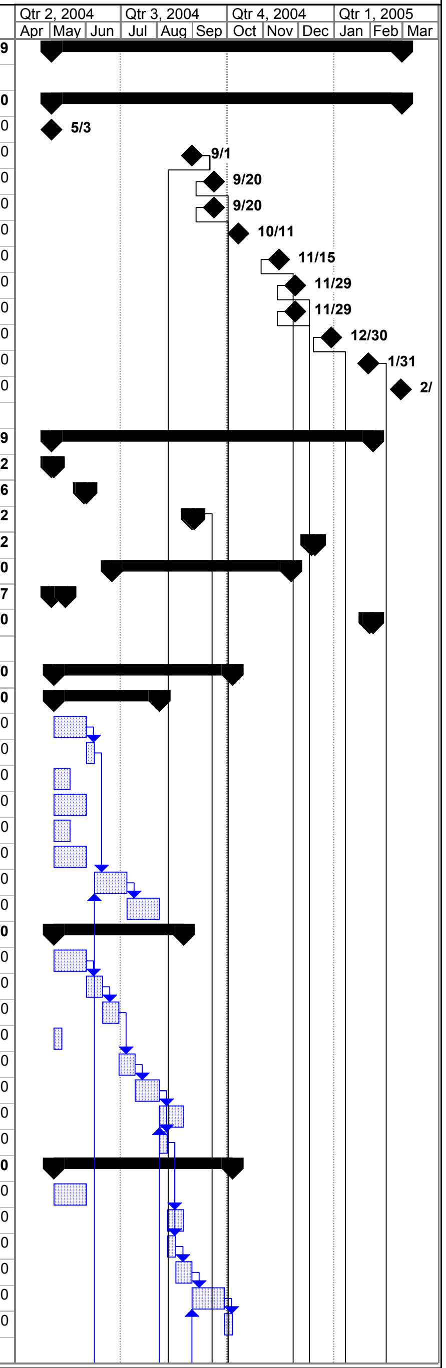
15 Appendix E: Detailed WBS

Notes on the WBS:

- The start date on the schedule is 5/3/04; if the actual start date is different, the entire schedule will be adjusted accordingly.
- The CoDR date (WBS1.1.10) is approximate, depending on Gemini's schedule.
- The completion of all work date (WBS1.1.11) depends on the CoDR date.
- There are some tasks in the Documents And Final Instrument Proposal section of the WBS (1.16) that do not have dollar amounts associated with them. These tasks are either implicit in the overall Conceptual Design process (WBS 1.16.1 and 1.16.3) or are covered under management hours (e.g., 1.16.8, 1.16.12, 1.16.13, etc.).
- At the mid-term review, a decision will be made as to which science instrument to pursue for the remainder of the project, the Multi-Wavelength Imager (MWI) or the Integral Field Unit (IFU). The costs for both options are shown in the WBS, with a negativx10-value task (1.12.2.6) added to the MWI to reflect the fact that only one will be funded.
- Depending on which science instrument is selected, the Gemini partner shares for the direct Gemini funding of this conceptual design will either be 33% U.S.A., 67% Canada (if the IFU is chosen) or 20% U.S.A., 80% Canada (if the MWI is chosen). During the ExAOC construction phase, of course, the partner shares will reflect the overall effort with the majority being in the U.S.A.

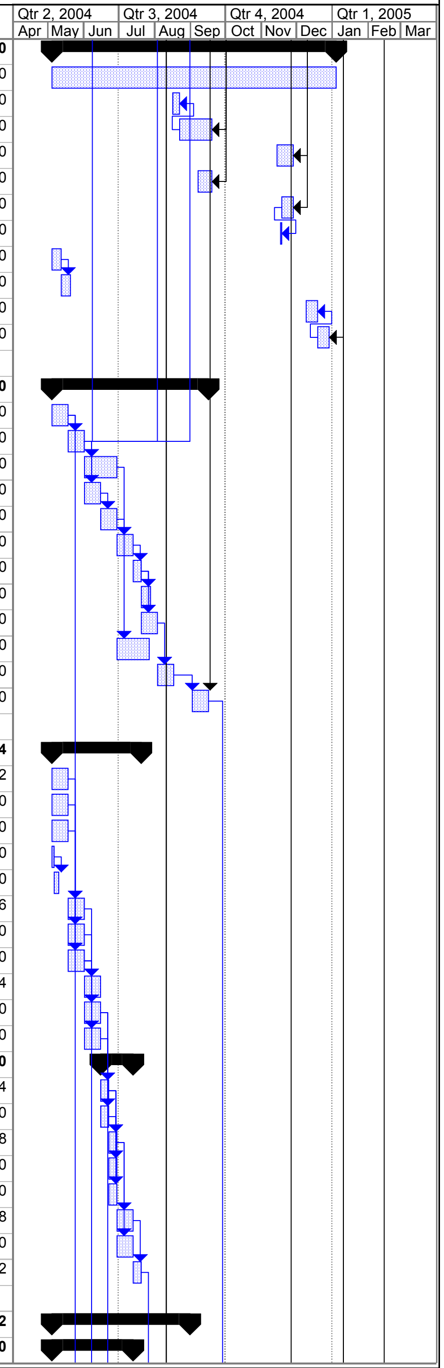
ExAOC Conceptual Design Work Breakdown Structure

ID	WBS	Task Name	Work	Start	Finish	Resource Names	Gemini Cost	TOTAL Cost
1	**1**	**ExAOC Conceptual Design**	**16,266.6 hrs**	**5/3/04**	**2/28/05**		**$199,880.00**	**$1,142,713.29**
2								
3	**1.1**	**Project Milestones**	**0 hrs**	**5/3/04**	**2/28/05**		**$0.00**	**$0.00**
4	1.1.1	Commence work	0 hrs	5/3/04	5/3/04		$0.00	$0.00
5	1.1.2	Down-select science instrument	0 hrs	9/1/04	9/1/04		$0.00	$0.00
6	1.1.3	Deliver draft of Initial OCDD	0 hrs	9/20/04	9/20/04		$0.00	$0.00
7	1.1.4	Deliver draft of Initial FPRD	0 hrs	9/20/04	9/20/04		$0.00	$0.00
8	1.1.5	Submit Design Study Documentation Outline	0 hrs	10/11/04	10/11/04		$0.00	$0.00
9	1.1.6	Deliver preliminary WBS, schedule, and budget	0 hrs	11/15/04	11/15/04		$0.00	$0.00
10	1.1.7	Deliver revised Initial OCDD	0 hrs	11/29/04	11/29/04		$0.00	$0.00
11	1.1.8	Deliver revised Initial FPRD	0 hrs	11/29/04	11/29/04		$0.00	$0.00
12	1.1.9	Deliver Design Study Documentation	0 hrs	12/30/04	12/30/04		$0.00	$0.00
13	1.1.10	Conceptual Design Study Review (CoDR)	0 hrs	1/31/05	1/31/05		$0.00	$0.00
14	1.1.11	Completion of all work	0 hrs	2/28/05	2/28/05		$0.00	$0.00
15								
16	**1.2**	**Meetings And Travel**	**2,096 hrs**	**5/3/04**	**2/3/05**		**$31,357.77**	**$184,876.49**
17	**1.2.1**	**kick-off workshop @ UCSC**	**400 hrs**	**5/3/04**	**5/4/04**		**$3,780.00**	**$33,002.32**
22	**1.2.2**	**science workshop @UCB**	**240 hrs**	**5/31/04**	**6/1/04**		**$4,649.00**	**$18,745.16**
25	**1.2.3**	**mid-term review @ HIA**	**384 hrs**	**9/1/04**	**9/2/04**		**$3,980.00**	**$35,512.32**
31	**1.2.4**	**pre-CoDR @ UCSC**	**360 hrs**	**12/13/04**	**12/15/04**		**$5,110.00**	**$31,237.52**
36	**1.2.5**	**monthly status**	**480 hrs**	**6/24/04**	**11/25/04**		**$4,725.00**	**$31,240.40**
52	**1.2.6**	**other**	**160 hrs**	**5/3/04**	**5/14/04**		**$1,598.77**	**$25,118.77**
58	**1.2.7**	**CoDR**	**72 hrs**	**2/1/05**	**2/3/05**		**$7,515.00**	**$10,020.00**
62								
63	**1.3**	**Science Case**	**646 hrs**	**5/5/04**	**10/5/04**		**$0.00**	**$30,005.20**
64	**1.3.1**	**direct imaging of young exoplanets**	**270 hrs**	**5/5/04**	**8/3/04**		**$0.00**	**$13,085.20**
65	1.3.1.1	estimate the distribution of young planets	40 hrs	5/5/04	6/1/04	Graham[25%]	$0.00	$1,800.00
66	1.3.1.2	evaluate the uncertainties in this distribution	10 hrs	6/2/04	6/8/04	Graham[25%]	$0.00	$450.00
67	1.3.1.3	construct a catalog	40 hrs	5/5/04	5/18/04	Patience[25%],Song[	$0.00	$1,800.00
68	1.3.1.4	develop detection techniques for ExAOC data	40 hrs	5/5/04	6/1/04	Doyon[25%]	$0.00	$2,000.00
69	1.3.1.5	develop methods and algorithms for measurement of orbital elements	20 hrs	5/5/04	5/18/04	Marcy[25%]	$0.00	$900.00
70	1.3.1.6	optimize the spectroscopy capabilities of the science instrument	40 hrs	5/5/04	6/1/04	Oppenheimer[25%]	$0.00	$2,535.20
71	1.3.1.7	design the planet search observing programs	40 hrs	6/9/04	7/6/04	Graham[25%]	$0.00	$1,800.00
72	1.3.1.8	summarize desired instrument specsand generate design-trade tools	40 hrs	7/7/04	8/3/04	Graham[25%]	$0.00	$1,800.00
73	**1.3.2**	**imaging of debris disks**	**200 hrs**	**5/5/04**	**8/24/04**		**$0.00**	**$9,000.00**
74	1.3.2.1	construct a tool kit for simulating images (including polarization)	40 hrs	5/5/04	6/1/04	Kalas[25%]	$0.00	$1,800.00
75	1.3.2.2	develop methodology for optical detection of disks	20 hrs	6/2/04	6/15/04	Kalas[25%]	$0.00	$900.00
76	1.3.2.3	develop algorithms for determination of disk properties	20 hrs	6/16/04	6/29/04	Kalas[25%]	$0.00	$900.00
77	1.3.2.4	explore how planetary signatures are imprinted on detected disks	30 hrs	5/5/04	5/11/04	Chiang[25%],Wu[25%	$0.00	$1,350.00
78	1.3.2.5	construct the catalog of target stars for debris disk imaging	20 hrs	6/30/04	7/13/04	Kalas[25%]	$0.00	$900.00
79	1.3.2.6	design the debris disk observing programs	30 hrs	7/14/04	8/3/04	Kalas[25%]	$0.00	$1,350.00
80	1.3.2.7	summarize desired instrument specs and generate design-trade tools	30 hrs	8/4/04	8/24/04	Kalas[25%]	$0.00	$1,350.00
81	1.3.2.8	summarize desired instrument specs and generate design-trade tools, 2	10 hrs	8/4/04	8/10/04	Graham[25%]	$0.00	$450.00
82	**1.3.3**	**adjunct science program**	**176 hrs**	**5/5/04**	**10/5/04**		**$0.00**	**$7,920.00**
83	1.3.3.1	solar system science	40 hrs	5/5/04	6/1/04	Marchis[25%]	$0.00	$1,800.00
84	1.3.3.2	evolved stars	20 hrs	8/11/04	8/24/04	Chiang[25%]	$0.00	$900.00
85	1.3.3.3	evolved stars, 2	20 hrs	8/11/04	8/17/04	Graham[25%],Johnst	$0.00	$900.00
86	1.3.3.4	extragalactic science: structure of AGN torii	20 hrs	8/18/04	8/31/04	Graham[25%]	$0.00	$900.00
87	1.3.3.5	design associated observing programs	56 hrs	9/1/04	9/28/04	Marchis[25%],Grahar	$0.00	$2,520.00
88	1.3.3.6	summarize desired instrument specs and generate design-trade tools	20 hrs	9/29/04	10/5/04	Marchis[25%],Grahar	$0.00	$900.00
89								



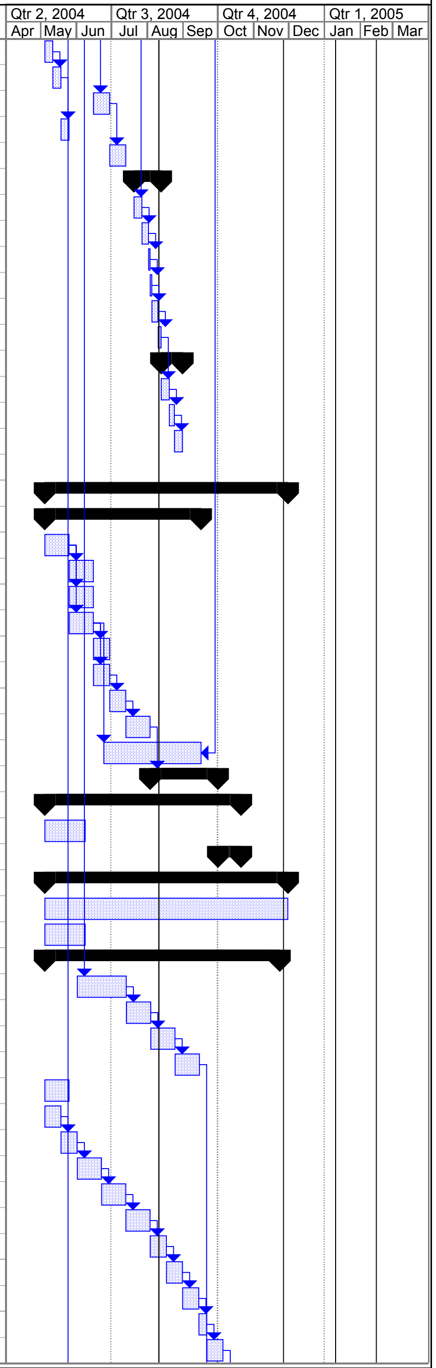
ExAOC Conceptual Design Work Breakdown Structure

ID	WBS	Task Name	Work	Start	Finish	Resource Names	Gemini Cost	TOTAL Cost
90	**1.4**	**System Engineering**	**508.4 hrs**	**5/5/04**	**1/4/05**		**$29,983.50**	**$51,738.00**
91	1.4.1	general system oversight	70 hrs	5/5/04	1/4/05	Murowinski[5%]	$6,300.00	$8,400.00
92	1.4.2	OCDD development	16 hrs	8/17/04	8/23/04	Murowinski[50%]	$1,440.00	$1,920.00
93	1.4.3	draft initial OCDD	80 hrs	8/23/04	9/20/04	Macintosh[50%]	$0.00	$7,840.00
94	1.4.4	revision to final OCDD	40 hrs	11/15/04	11/29/04	Macintosh[50%]	$0.00	$3,920.00
95	1.4.5	draft initial FPRD	62.4 hrs	9/8/04	9/20/04	Murowinski[60%],Bar	$4,738.50	$6,318.00
96	1.4.6	revision to final FPRD	48 hrs	11/19/04	11/29/04	Murowinski[50%],Bar	$3,442.50	$4,590.00
97	1.4.7	compliance matricies	8 hrs	11/18/04	11/19/04	Baril	$427.50	$570.00
98	1.4.8	review of reuse of Gemini designs	24 hrs	5/5/04	5/12/04	Murowinski[50%]	$2,160.00	$2,880.00
99	1.4.9	ICD assessment	48 hrs	5/13/04	5/20/04	Murowinski[50%],Bar	$3,442.50	$4,590.00
100	1.4.10	summary of key analyses and trades	48 hrs	12/10/04	12/20/04	Murowinski[50%],Bar	$3,442.50	$4,590.00
101	1.4.11	final document preparation and review	64 hrs	12/20/04	12/30/04	Murowinski[50%],Bar	$4,590.00	$6,120.00
102								
103	**1.5**	**Error Budget And Performance Analysis**	**748 hrs**	**5/5/04**	**9/16/04**		**$2,160.00**	**$43,807.20**
104	1.5.1	determine speckle lifetime for various noise sources	40 hrs	5/5/04	5/18/04	Macintosh[50%]	$0.00	$3,920.00
105	1.5.2	generate analytic error budget	40 hrs	5/19/04	6/1/04	Macintosh[50%]	$0.00	$3,920.00
106	1.5.3	integrate multiwavelength imaging into error budgets	80 hrs	6/2/04	6/29/04	Marois[50%]	$0.00	$0.00
107	1.5.4	use full AO simulations to design noise model for Fourier simulations	80 hrs	6/2/04	6/15/04	Macintosh[50%],Poy	$0.00	$7,240.00
108	1.5.5	use analytic simulations to map out d/dt/magnitude space	40 hrs	6/16/04	6/29/04	Macintosh[50%]	$0.00	$3,920.00
109	1.5.6	validate analytic simulations against Fourier simulation	40 hrs	6/30/04	7/13/04	Macintosh[50%]	$0.00	$3,920.00
110	1.5.7	generate long-exposure Fourier simulations for selected cases	4 hrs	7/14/04	7/20/04	Macintosh[10%]	$0.00	$392.00
111	1.5.8	optomechanical error budgets	24 hrs	7/21/04	7/28/04	Murowinski[50%]	$2,160.00	$2,880.00
112	1.5.9	generate error budget for optical system	160 hrs	7/21/04	8/3/04	Macintosh[50%],Bau	$0.00	$7,240.00
113	1.5.10	explore additional error sources (chromatic, scintillation, etc.)	80 hrs	6/30/04	7/27/04	Marois[50%]	$0.00	$0.00
114	1.5.11	add additional error sources to analytic and Fourier models	40 hrs	8/4/04	8/17/04	Macintosh[50%]	$0.00	$3,920.00
115	1.5.12	generate complete error/performance budget for strawman design	120 hrs	9/3/04	9/16/04	Macintosh[50%],Opp	$0.00	$6,455.20
116								
117	**1.6**	**Overall Computer Architecture**	**524 hrs**	**5/5/04**	**7/20/04**		**$20,452.50**	**$44,051.44**
118	1.6.1	identify preliminary requirements for the overall computer system, U	32 hrs	5/5/04	5/18/04	Deich[40%]	$0.00	$2,248.32
119	1.6.2	identify preliminary requirements for the overall computer system	8 hrs	5/5/04	5/18/04	Palmer[10%]	$0.00	$784.00
120	1.6.3	identify preliminary requirements for the overall computer system, H	32 hrs	5/5/04	5/18/04	Dunn[40%]	$2,340.00	$3,120.00
121	1.6.4	decide whether to base CoD on Linux or another OS	8 hrs	5/5/04	5/6/04	Palmer[50%]	$0.00	$784.00
122	1.6.5	decide whether to base CoD on new API or EPICS interface	8 hrs	5/7/04	5/10/04	Palmer[50%]	$0.00	$784.00
123	1.6.6	investigate reuse of existing computer HW/SW, U	16 hrs	5/19/04	6/1/04	Deich[20%]	$0.00	$1,124.16
124	1.6.7	investigate reuse of existing computer HW/SW	20 hrs	5/19/04	6/1/04	Palmer[25%]	$0.00	$1,960.00
125	1.6.8	investigate reuse of existing computer HW/SW, H	120 hrs	5/19/04	6/1/04	Dunn[50%],Saddlem	$8,775.00	$11,700.00
126	1.6.9	develop preliminary system data flows, U	24 hrs	6/2/04	6/15/04	Deich[30%]	$0.00	$1,686.24
127	1.6.10	develop preliminary system data flows	8 hrs	6/2/04	6/15/04	Palmer[10%]	$0.00	$784.00
128	1.6.11	develop preliminary system data flows, H	40 hrs	6/2/04	6/15/04	Wooff[50%]	$2,137.50	$2,850.00
129	**1.6.12**	**define preliminary HW/SW interfaces between subsystems:**	**176 hrs**	**6/16/04**	**7/13/04**		**$7,200.00**	**$13,978.40**
130	1.6.12.1	Supervisor and components controller (software only)	24 hrs	6/16/04	6/22/04	Deich[60%]	$0.00	$1,686.24
131	1.6.12.2	Supervisor and components controller (software only), H	40 hrs	6/16/04	6/22/04	Wooff	$2,137.50	$2,850.00
132	1.6.12.3	Supervisor and AO Computer (SCC/AOC), U	8 hrs	6/23/04	6/29/04	Deich[20%]	$0.00	$562.08
133	1.6.12.4	Supervisor and AO Computer (SCC/AOC)	16 hrs	6/23/04	6/29/04	Palmer[40%]	$0.00	$1,568.00
134	1.6.12.5	Supervisor and AO Computer (SCC/AOC), H	40 hrs	6/23/04	6/29/04	Wooff	$2,137.50	$2,850.00
135	1.6.12.6	Supervisor and Science Instrument Computer (SCC/SIC)	8 hrs	6/30/04	7/13/04	Deich[10%]	$0.00	$562.08
136	1.6.12.7	Supervisor and Science Instrument Computer (SCC/SIC), H	40 hrs	6/30/04	7/13/04	Dunn[50%]	$2,925.00	$3,900.00
137	1.6.13	as necessary, create prototype implementations for testing	32 hrs	7/14/04	7/20/04	Deich[80%]	$0.00	$2,248.32
138								
139	**1.7**	**Supervisory / Components Controller Computer (SCC)**	**392 hrs**	**5/5/04**	**8/31/04**		**$12,262.50**	**$29,839.92**
140	**1.7.1**	**Supervisor**	**200 hrs**	**5/5/04**	**7/13/04**		**$12,262.50**	**$16,350.00**



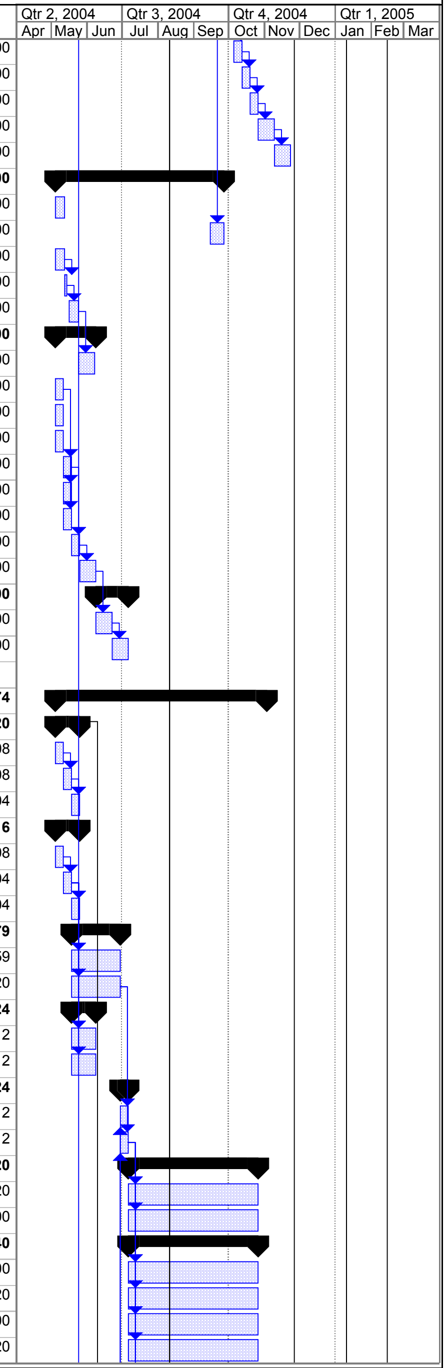
ExAOC Conceptual Design Work Breakdown Structure

ID	WBS	Task Name	Work	Start	Finish	Resource Names	Gemini Cost	TOTAL Cost
141	1.7.1.1	identify preliminary software requirements for the Supervisor	40 hrs	5/5/04	5/11/04	Wooff	$2,137.50	$2,850.00
142	1.7.1.2	identify actions required for all top level sequence commands	40 hrs	5/12/04	5/18/04	Wooff	$2,137.50	$2,850.00
143	1.7.1.3	define a preliminary ExAOC to DHS interface	40 hrs	6/16/04	6/29/04	Dunn[50%]	$2,925.00	$3,900.00
144	1.7.1.4	identify data required from the TCS or SIR records within Gemini	40 hrs	5/19/04	5/25/04	Wooff	$2,137.50	$2,850.00
145	1.7.1.5	define a preliminary interface with the telescope	40 hrs	6/30/04	7/13/04	Saddlemyer[50%]	$2,925.00	$3,900.00
146	**1.7.2**	**Components Controller**	**112 hrs**	**7/21/04**	**8/13/04**		**$0.00**	**$7,869.12**
147	1.7.2.1	identify prelim. SW requirements for the Components Controller	32 hrs	7/21/04	7/27/04	Deich[80%]	$0.00	$2,248.32
148	1.7.2.2	identify component control requirements, especially precision and rate	24 hrs	7/28/04	8/2/04	Deich[80%]	$0.00	$1,686.24
149	1.7.2.3	evaluate competing motion controllers	8 hrs	8/2/04	8/3/04	Deich[80%]	$0.00	$562.08
150	1.7.2.4	evaluate competing controller boards	8 hrs	8/4/04	8/5/04	Deich[80%]	$0.00	$562.08
151	1.7.2.5	identify unusual control issues and specify solutions	24 hrs	8/5/04	8/10/04	Deich[80%]	$0.00	$1,686.24
152	1.7.2.6	investigate motion controller hardware/software reuse	16 hrs	8/11/04	8/13/04	Deich[80%]	$0.00	$1,124.16
153	**1.7.3**	**Engineering User Interface**	**80 hrs**	**8/13/04**	**8/31/04**		**$0.00**	**$5,620.80**
154	1.7.3.1	identify prelim. SW requirements for the Engineering UI	32 hrs	8/13/04	8/20/04	Deich[80%]	$0.00	$2,248.32
155	1.7.3.2	ensure that all aspects of the computer system will support a UI	16 hrs	8/20/04	8/24/04	Deich[80%]	$0.00	$1,124.16
156	1.7.3.3	in conjunction with others, develop a strawman UI	32 hrs	8/25/04	8/31/04	Deich[80%]	$0.00	$2,248.32
157								
158	**1.8**	**Adaptive Optics System**	**3,084.8 hrs**	**5/5/04**	**11/30/04**		**$3,600.00**	**$172,249.59**
159	**1.8.1**	**AO optical conceptual design, including WFS**	**270 hrs**	**5/5/04**	**9/16/04**		**$0.00**	**$22,410.00**
160	1.8.1.1	with science inst. developers, identify AO relay and WFS requs.	30 hrs	5/5/04	5/25/04	Bauman[25%]	$0.00	$2,490.00
161	1.8.1.2	design optics for AO relay and WFS	60 hrs	5/26/04	6/15/04	Bauman[50%]	$0.00	$4,980.00
162	1.8.1.3	identify candidate vendors for optical components	10 hrs	5/26/04	6/15/04	Bauman[8%]	$0.00	$830.00
163	1.8.1.4	estimate optical train emissivity and throughput	10 hrs	5/26/04	6/15/04	Bauman[8%]	$0.00	$830.00
164	1.8.1.5	tolerance AO relay and WFS	30 hrs	6/16/04	6/29/04	Bauman[38%]	$0.00	$2,490.00
165	1.8.1.6	establish optic mounting schemes and requirements	40 hrs	6/16/04	6/29/04	Bauman[50%]	$0.00	$3,320.00
166	1.8.1.7	sketch alignment procedure	30 hrs	6/30/04	7/13/04	Bauman[38%]	$0.00	$2,490.00
167	1.8.1.8	evaluate technical, cost, and schedule risks	20 hrs	7/14/04	8/3/04	Bauman[17%]	$0.00	$1,660.00
168	1.8.1.9	write optical design/tolerancing document	40 hrs	6/25/04	9/16/04	Bauman[8%]	$0.00	$3,320.00
169	**1.8.2**	**AO mechanical conceptual design**	**186 hrs**	**8/4/04**	**10/1/04**		**$0.00**	**$9,897.06**
187	**1.8.3**	**WFS**	**116.8 hrs**	**5/5/04**	**10/21/04**		**$0.00**	**$8,006.53**
188	1.8.3.1	investigate candidate CCDs	40 hrs	5/5/04	6/8/04	Palmer[20%]	$0.00	$3,920.00
189	**1.8.3.2**	**WFS mechanical conceptual design**	**76.8 hrs**	**10/1/04**	**10/21/04**		**$0.00**	**$4,086.53**
200	**1.8.4**	**DM**	**1,240 hrs**	**5/5/04**	**11/30/04**		**$0.00**	**$21,140.00**
201	1.8.4.1	4k MEMS feasibility study	1,200 hrs	5/5/04	11/30/04	BMC	$0.00	$17,220.00
202	1.8.4.2	investigate alternative DMs	40 hrs	5/5/04	6/8/04	Palmer[20%]	$0.00	$3,920.00
203	**1.8.5**	**Algorithms**	**900 hrs**	**5/5/04**	**11/23/04**		**$0.00**	**$73,490.00**
204	1.8.5.1	investigate issue of invisible mode filtering and cleaning	80 hrs	6/2/04	7/14/04	Veran2[33%]	$0.00	$7,800.00
205	1.8.5.2	investigate need / feasibility of modal gain optimization	40 hrs	7/14/04	8/4/04	Veran2[33%]	$0.00	$3,900.00
206	1.8.5.3	investigate splitting wave-front correction between 2 DMs & TTM	40 hrs	8/4/04	8/25/04	Veran2[33%]	$0.00	$3,900.00
207	1.8.5.4	investigate adaptive predictors	40 hrs	8/25/04	9/15/04	Veran2[33%]	$0.00	$3,900.00
208	1.8.5.5	Lavigne effort	120 hrs	5/5/04	5/25/04	Lavigne	$0.00	$5,850.00
209	1.8.5.6	develop automated calibration for MEMS device	40 hrs	5/5/04	5/18/04	Poyneer[50%]	$0.00	$3,320.00
210	1.8.5.7	use automation to fully characterize MEMS device	40 hrs	5/19/04	6/1/04	Poyneer[50%]	$0.00	$3,320.00
211	1.8.5.8	study impact of actuators outside of aperture	60 hrs	6/2/04	6/22/04	Poyneer[50%]	$0.00	$4,980.00
212	1.8.5.9	study impact of clipping of actuators due to large aberrations	60 hrs	6/23/04	7/13/04	Poyneer[50%]	$0.00	$4,980.00
213	1.8.5.10	study impact of dead of actuators on the MEMS	60 hrs	7/14/04	8/3/04	Poyneer[50%]	$0.00	$4,980.00
214	1.8.5.11	discuss hidden modes, FTR mode space, software issues with HIA	40 hrs	8/4/04	8/17/04	Poyneer[50%]	$0.00	$3,320.00
215	1.8.5.12	design FTR filters	40 hrs	8/18/04	8/31/04	Poyneer[50%]	$0.00	$3,320.00
216	1.8.5.13	study FTR noise propagation	40 hrs	9/1/04	9/14/04	Poyneer[50%]	$0.00	$3,320.00
217	1.8.5.14	incorporate FTR to frequency-domain modeling	20 hrs	9/15/04	9/21/04	Poyneer[50%]	$0.00	$1,660.00
218	1.8.5.15	analyze quadcell gain changes in closed loop	40 hrs	9/22/04	10/5/04	Poyneer[50%]	$0.00	$3,320.00



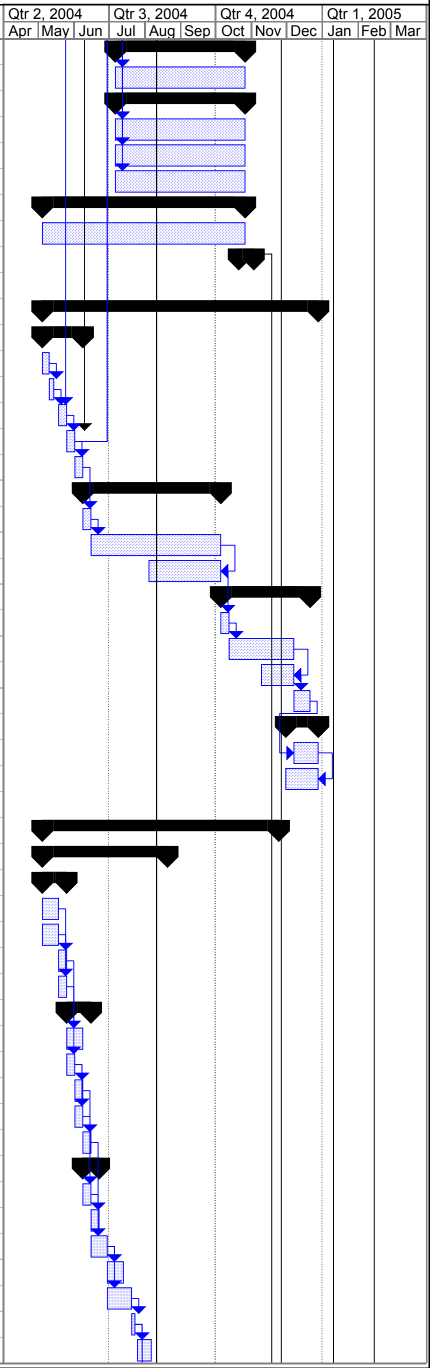
ExAOC Conceptual Design Work Breakdown Structure

ID	WBS	Task Name	Work	Start	Finish	Resource Names	Gemini Cost	TOTAL Cost
219	1.8.5.16	spec out total computational burden for end-to-end simulation	20 hrs	10/6/04	10/12/04	Poyneer[50%]	$0.00	$1,660.00
220	1.8.5.17	install Arroyo locally and run sample simulations as provided in suite	20 hrs	10/13/04	10/19/04	Poyneer[50%]	$0.00	$1,660.00
221	1.8.5.18	evaluate simulation options and time requirements	20 hrs	10/20/04	10/26/04	Poyneer[50%]	$0.00	$1,660.00
222	1.8.5.19	write improved MEMS module for simulations	40 hrs	10/27/04	11/9/04	Poyneer[50%]	$0.00	$3,320.00
223	1.8.5.20	write improved WFS module for simulations	40 hrs	11/10/04	11/23/04	Poyneer[50%]	$0.00	$3,320.00
224	**1.8.6**	**Adaptive Optics Computer (AOC)**	**100 hrs**	**5/5/04**	**9/27/04**		**$0.00**	**$9,790.00**
225	1.8.6.1	identify all probable capabilities that the AOC will have to have	24 hrs	5/5/04	5/12/04	Palmer[50%]	$0.00	$2,352.00
226	1.8.6.2	identify diagnostic/telemetry data	20 hrs	9/15/04	9/27/04	Veran2[33%]	$0.00	$1,950.00
227	1.8.6.3	refine computational requirements for AOC capabilities	24 hrs	5/5/04	5/12/04	Palmer[50%]	$0.00	$2,352.00
228	1.8.6.4	produce a timing diagram for AOC capabilities	8 hrs	5/13/04	5/14/04	Palmer[50%]	$0.00	$784.00
229	1.8.6.5	refine internal interface requirements (i.e., bus requirements)	24 hrs	5/17/04	5/24/04	Palmer[50%]	$0.00	$2,352.00
230	**1.8.7**	**Adaptive Optics Computer (AOC) Software**	**192 hrs**	**5/5/04**	**6/8/04**		**$3,600.00**	**$19,676.00**
231	1.8.7.1	identify preliminary software requirements for the AOC	32 hrs	5/25/04	6/7/04	Palmer[40%]	$0.00	$3,136.00
232	1.8.7.2	identify and diagram software processes	10 hrs	5/5/04	5/11/04	Palmer[25%]	$0.00	$980.00
233	1.8.7.3	identify and diagram software processes, H	20 hrs	5/5/04	5/11/04	Veran2[50%]	$0.00	$1,950.00
234	1.8.7.4	identify and diagram software processes, H2	20 hrs	5/5/04	5/11/04	Herriot[50%]	$1,800.00	$2,400.00
235	1.8.7.5	define and document preliminary inter-process data-flows	10 hrs	5/12/04	5/18/04	Palmer[25%]	$0.00	$980.00
236	1.8.7.6	define and document preliminary inter-process data-flows, H	20 hrs	5/12/04	5/18/04	Veran2[50%]	$0.00	$1,950.00
237	1.8.7.7	define and document preliminary inter-process data-flows, H2	20 hrs	5/12/04	5/18/04	Herriot[50%]	$1,800.00	$2,400.00
238	1.8.7.8	produce preliminary high-level structure charts for processes	20 hrs	5/19/04	5/25/04	Palmer[50%]	$0.00	$1,960.00
239	1.8.7.9	as necessary, produce and test prototype code	40 hrs	5/26/04	6/8/04	Palmer[50%]	$0.00	$3,920.00
240	**1.8.8**	**Adaptive Optics Computer (AOC) Hardware**	**80 hrs**	**6/9/04**	**7/6/04**		**$0.00**	**$7,840.00**
241	1.8.8.1	specify a preliminary hardware design (to establish feasibility)	40 hrs	6/9/04	6/22/04	Palmer[50%]	$0.00	$3,920.00
242	1.8.8.2	as necessary, run prototype code on a simplified hardware	40 hrs	6/23/04	7/6/04	Palmer[50%]	$0.00	$3,920.00
243								
244	**1.9**	**Coronagraph**	**929.2 hrs**	**5/5/04**	**11/3/04**		**$0.00**	**$62,914.74**
245	**1.9.1**	**determine dynamic range of four coronagraph designs**	**88 hrs**	**5/5/04**	**5/25/04**		**$0.00**	**$5,645.20**
246	1.9.1.1	choice of initial 4 designs	32 hrs	5/5/04	5/11/04	Sivaramakrishnan[20	$0.00	$2,028.08
247	1.9.1.2	create input & output descriptions for simulations	32 hrs	5/12/04	5/18/04	Sivaramakrishnan[20	$0.00	$2,062.08
248	1.9.1.3	assemble each coronagraph simulation	24 hrs	5/19/04	5/25/04	Sivaramakrishnan[20	$0.00	$1,555.04
249	**1.9.2**	**simple data reduction pipeline to produce dynamic range**	**80 hrs**	**5/5/04**	**5/25/04**		**$0.00**	**$4,840.16**
250	1.9.2.1	design dynamic range script	32 hrs	5/5/04	5/11/04	Sivaramakrishnan[20	$0.00	$2,062.08
251	1.9.2.2	write dynamic range script	24 hrs	5/12/04	5/18/04	Makidon[20%],Soum	$0.00	$1,389.04
252	1.9.2.3	test dynamic range script on existing test files	24 hrs	5/19/04	5/25/04	Makidon[20%],Soum	$0.00	$1,389.04
253	**1.9.3**	**investigate optics, stop and apodizer tolerances**	**100 hrs**	**5/19/04**	**6/29/04**		**$0.00**	**$7,118.79**
254	1.9.3.1	spot and apodizer numerical tolerancing	52 hrs	5/19/04	6/29/04	Sivaramakrishnan[7%	$0.00	$3,295.59
255	1.9.3.2	optical alignment tolerancing	48 hrs	5/19/04	6/29/04	Makidon[3%],Sivarar	$0.00	$3,823.20
256	**1.9.4**	**investigate stop and apodizer fabrication**	**48 hrs**	**5/19/04**	**6/8/04**		**$0.00**	**$3,042.24**
257	1.9.4.1	identify and contact companies	24 hrs	5/19/04	6/8/04	Oppenheimer[20%]	$0.00	$1,521.12
258	1.9.4.2	write specifications for quotes	24 hrs	5/19/04	6/8/04	Oppenheimer[20%]	$0.00	$1,521.12
259	**1.9.5**	**downselect to 2 designs**	**48 hrs**	**6/30/04**	**7/6/04**		**$0.00**	**$3,540.24**
260	1.9.5.1	design presentation to project	24 hrs	6/30/04	7/6/04	Oppenheimer[60%]	$0.00	$1,521.12
261	1.9.5.2	write up design choices, outline tech challenges for each of 2	24 hrs	6/30/04	7/6/04	Sivaramakrishnan[60	$0.00	$2,019.12
262	**1.9.6**	**ZEMAX optical design**	**80 hrs**	**7/7/04**	**10/26/04**		**$0.00**	**$4,825.20**
263	1.9.6.1	design 1	40 hrs	7/7/04	10/26/04	Oppenheimer[6%]	$0.00	$2,535.20
264	1.9.6.2	design 2	40 hrs	7/7/04	10/26/04	Makidon[6%]	$0.00	$2,290.00
265	**1.9.7**	**optical simulation of detailed designs**	**136 hrs**	**7/7/04**	**10/26/04**		**$0.00**	**$9,766.40**
266	1.9.7.1	interfacing with End-to-End simulations	16 hrs	7/7/04	10/26/04	Makidon[3%]	$0.00	$916.00
267	1.9.7.2	scintillation, polarization effects: quantitative estimation	40 hrs	7/7/04	10/26/04	Sivaramakrishnan[6%	$0.00	$3,365.20
268	1.9.7.3	design 1	40 hrs	7/7/04	10/26/04	Soummer[6%]	$0.00	$2,120.00
269	1.9.7.4	design 2	40 hrs	7/7/04	10/26/04	Sivaramakrishnan[6%	$0.00	$3,365.20



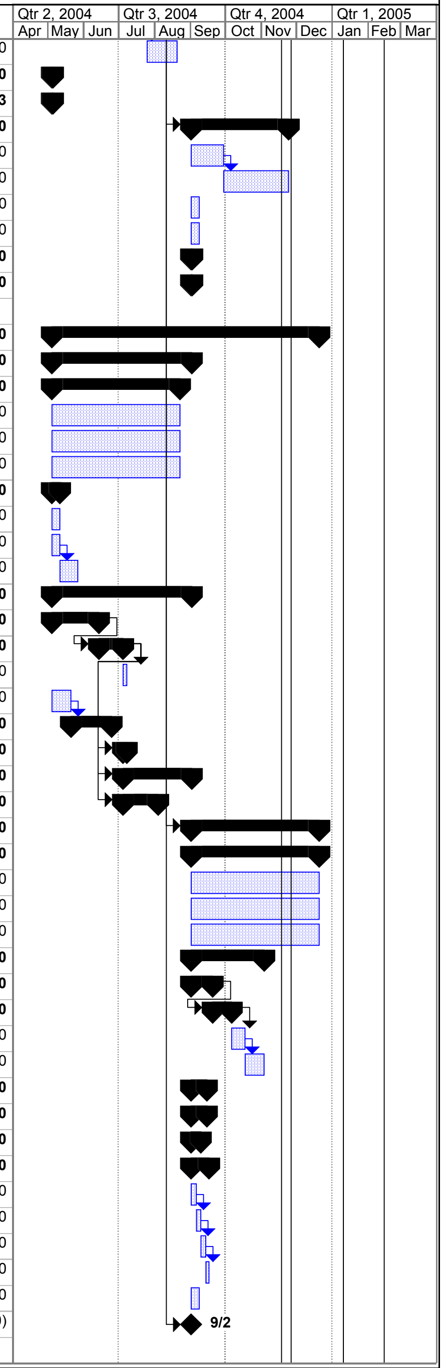
ExAOC Conceptual Design Work Breakdown Structure

ID	WBS	Task Name	Work	Start	Finish	Resource Names	Gemini Cost	TOTAL Cost
270	**1.9.8**	**dynamic range predictions**	**89.6 hrs**	**7/7/04**	**10/26/04**		**$0.00**	**$5,075.20**
271	1.9.8.1	data reduction of simulated data	89.6 hrs	7/7/04	10/26/04	Makidon[12%],Soum	$0.00	$5,075.20
272	**1.9.9**	**estimating simulation errors from critical components**	**70 hrs**	**7/7/04**	**10/26/04**		**$0.00**	**$4,643.90**
273	1.9.9.1	phase errors from apodizers	20 hrs	7/7/04	10/26/04	Soummer[3%]	$0.00	$1,060.00
274	1.9.9.2	phase errors from stops	20 hrs	7/7/04	10/26/04	Digby[3%]	$0.00	$1,060.00
275	1.9.9.3	analytical/numerical tolerancing	30 hrs	7/7/04	10/26/04	Sivaramakrishnan[5	$0.00	$2,523.90
276	**1.9.10**	**proposal preparation and documentation**	**140 hrs**	**5/5/04**	**10/26/04**		**$0.00**	**$11,778.20**
277	1.9.10.1	reporting for the duration of project @4hr/wk	140 hrs	5/5/04	10/26/04	Sivaramakrishnan2[1	$0.00	$11,778.20
278	**1.9.11**	**coronagraph conceptual mechanical design**	**49.6 hrs**	**10/21/04**	**11/3/04**		**$0.00**	**$2,639.22**
286								
287	**1.10**	**Calibration**	**1,467.2 hrs**	**5/5/04**	**12/28/04**		**$0.00**	**$135,192.00**
288	**1.10.1**	**Subsystems Requirements, Definitions, and Interfaces**	**128.8 hrs**	**5/5/04**	**6/8/04**		**$0.00**	**$11,868.00**
289	1.10.1.1	Science Target Characteristics	22.4 hrs	5/5/04	5/10/04	WallaceKent[25%],G	$0.00	$2,064.00
290	1.10.1.2	Telescope Working Environment	22.4 hrs	5/11/04	5/14/04	WallaceKent[25%],G	$0.00	$2,064.00
291	1.10.1.3	Wavefront Sensor Error Budgets	28 hrs	5/19/04	5/25/04	WallaceKent[25%],G	$0.00	$2,580.00
292	1.10.1.4	Coronagraph Candidates	28 hrs	5/26/04	6/1/04	WallaceKent[25%],G	$0.00	$2,580.00
293	1.10.1.5	Calibration Stimulus Definition	28 hrs	6/2/04	6/8/04	WallaceKent[25%],G	$0.00	$2,580.00
294	**1.10.2**	**Calibration Simulation and Analysis**	**722.4 hrs**	**6/9/04**	**10/5/04**		**$0.00**	**$66,564.00**
295	1.10.2.1	Define interactions with other subsystem simulations	28 hrs	6/9/04	6/15/04	WallaceKent[25%],G	$0.00	$2,580.00
296	1.10.2.2	Stand-alone simulations of high contrast WFS methods	448 hrs	6/16/04	10/5/04	WallaceKent[25%],G	$0.00	$41,280.00
297	1.10.2.3	Integrated modeling of high contrast wave front sensor	246.4 hrs	8/5/04	10/5/04	WallaceKent[25%],G	$0.00	$22,704.00
298	**1.10.3**	**Evaluation and Ranking**	**420 hrs**	**10/6/04**	**12/21/04**		**$0.00**	**$38,700.00**
299	1.10.3.1	Post simulation requirements and interfaces review	28 hrs	10/6/04	10/12/04	WallaceKent[25%],G	$0.00	$2,580.00
300	1.10.3.2	Exercise simulations of wavefront sensor and calibrations	224 hrs	10/13/04	12/7/04	WallaceKent[25%],G	$0.00	$20,640.00
301	1.10.3.3	Laboratory test of calibration routines	112 hrs	11/10/04	12/7/04	WallaceKent[25%],G	$0.00	$10,320.00
302	1.10.3.4	Calibration ranking and evaluation	56 hrs	12/8/04	12/21/04	WallaceKent[25%],G	$0.00	$5,160.00
303	**1.10.4**	**Selection of leading wavefront sensor and calibration candidates**	**196 hrs**	**12/1/04**	**12/28/04**		**$0.00**	**$18,060.00**
304	1.10.4.1	Candidate selections	84 hrs	12/8/04	12/28/04	WallaceKent[25%],G	$0.00	$7,740.00
305	1.10.4.2	Written findings	112 hrs	12/1/04	12/28/04	WallaceKent[25%],G	$0.00	$10,320.00
306								
307	**1.11**	**Integral Field Unit (IFU)**	**1,336 hrs**	**5/5/04**	**11/24/04**		**$46,514.73**	**$67,174.73**
308	**1.11.1**	**Pre down-select**	**776 hrs**	**5/5/04**	**8/20/04**		**$17,349.33**	**$35,759.33**
309	**1.11.1.1**	**Work with coronagraph team**	**144 hrs**	**5/5/04**	**5/25/04**		**$3,457.20**	**$4,807.20**
310	1.11.1.1.1	determine Coronagraph and pupil locations	80 hrs	5/5/04	5/18/04	McElwain	$2,304.80	$2,304.80
311	1.11.1.1.2	determine Coronagraph and pupil locations, O	16 hrs	5/5/04	5/18/04	Larkin[20%]	$0.00	$900.00
312	1.11.1.1.3	rotating or non-rotating field	40 hrs	5/19/04	5/25/04	McElwain	$1,152.40	$1,152.40
313	1.11.1.1.4	rotating or non-rotating field, O	8 hrs	5/19/04	5/25/04	Larkin[20%]	$0.00	$450.00
314	**1.11.1.2**	**Sensitivity vs. resolution**	**208 hrs**	**5/26/04**	**6/15/04**		**$3,457.20**	**$9,687.20**
315	1.11.1.2.1	detector wavelength range	80 hrs	5/26/04	6/8/04	Larkin[20%],McLean[	$0.00	$5,780.00
316	1.11.1.2.2	atmospheric modelling - OH contamination	40 hrs	5/26/04	6/1/04	McElwain	$1,152.40	$1,152.40
317	1.11.1.2.3	backgrounds from sky and stars	40 hrs	6/2/04	6/8/04	McElwain	$1,152.40	$1,152.40
318	1.11.1.2.4	backgrounds from sky and stars, O	8 hrs	6/2/04	6/8/04	Larkin[20%]	$0.00	$450.00
319	1.11.1.2.5	spectral nulling vs. resolution	40 hrs	6/9/04	6/15/04	McElwain	$1,152.40	$1,152.40
320	**1.11.1.3**	**Slicing technique (lenslets?)**	**80 hrs**	**6/9/04**	**6/22/04**		**$0.00**	**$4,500.00**
321	1.11.1.3.1	spectral spacing (overlap)	40 hrs	6/9/04	6/15/04	Larkin	$0.00	$2,250.00
322	1.11.1.3.2	vendor capabilities (fill factor)	40 hrs	6/16/04	6/22/04	Larkin	$0.00	$2,250.00
323	1.11.1.4	polarimetry	80 hrs	6/16/04	6/29/04	McElwain	$2,304.80	$2,304.80
324	1.11.1.5	define basic sizes and characteristics	80 hrs	6/30/04	7/13/04	McElwain	$2,304.80	$2,304.80
325	1.11.1.6	define basic sizes and characteristics, O	48 hrs	6/30/04	7/20/04	Larkin[20%],McLean[	$0.00	$3,180.00
326	1.11.1.7	decide on reflective vs. refractive components	24 hrs	7/21/04	7/23/04	Larkin	$0.00	$1,350.00
327	1.11.1.8	modelling of spectrograph performance	80 hrs	7/26/04	8/6/04	McElwain	$2,304.80	$2,304.80



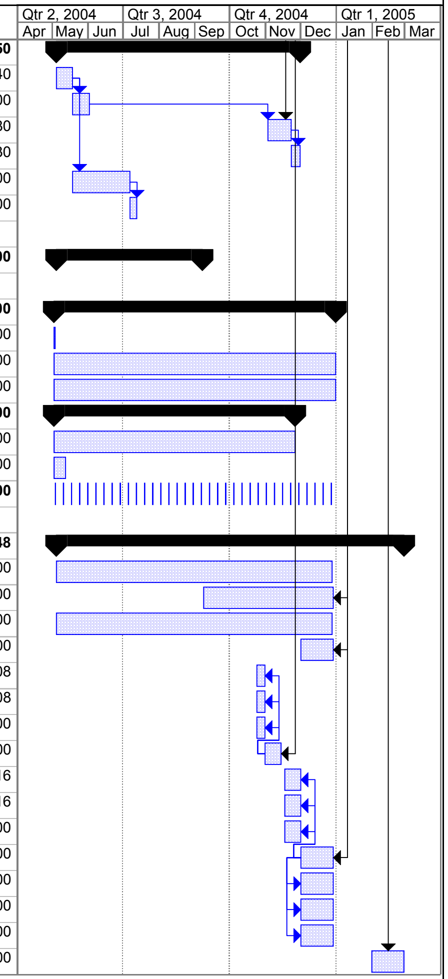
ExAOC Conceptual Design Work Breakdown Structure

ID	WBS	Task Name	Work	Start	Finish	Resource Names	Gemini Cost	TOTAL Cost
328	1.11.1.9	modelling of spectrograph performance, O	32 hrs	7/26/04	8/20/04	Larkin[20%]	$0.00	$1,800.00
329	**1.11.1.10**	**Travel**	**0 hrs**	**5/5/04**	**5/5/04**		**$2,448.00**	**$2,448.00**
331	**1.11.1.11**	**Miscellaneous**	**0 hrs**	**5/5/04**	**5/5/04**		**$1,072.53**	**$1,072.53**
335	**1.11.2**	**Post down-select**	**560 hrs**	**9/2/04**	**11/24/04**		**$29,165.40**	**$31,415.40**
336	1.11.2.1	sampling techniques (up-the-ramp)	160 hrs	9/2/04	9/29/04	Weiss	$9,592.00	$9,592.00
337	1.11.2.2	model flexures effect on sensitivity	320 hrs	9/30/04	11/24/04	Kress	$16,054.40	$16,054.40
338	1.11.2.3	measure scattering within OSIRIS	40 hrs	9/2/04	9/8/04	OSIRIS team	$0.00	$0.00
339	1.11.2.4	cost modelling of best model	40 hrs	9/2/04	9/8/04	Larkin	$0.00	$2,250.00
340	**1.11.2.5**	**Travel**	**0 hrs**	**9/2/04**	**9/2/04**		**$2,448.00**	**$2,448.00**
342	**1.11.2.6**	**Miscellaneous**	**0 hrs**	**9/2/04**	**9/2/04**		**$1,071.00**	**$1,071.00**
346								
347	**1.12**	**Multi-Wavelength Imager**	**2,180 hrs**	**5/5/04**	**12/21/04**		**$26,674.00**	**$130,863.00**
348	**1.12.1**	**Pre down-select**	**1,255 hrs**	**5/5/04**	**9/2/04**		**$26,674.00**	**$86,750.00**
349	**1.12.1.1**	**Project General**	**150 hrs**	**5/5/04**	**8/23/04**		**$4,500.00**	**$11,500.00**
350	1.12.1.1.1	Management (project)	50 hrs	5/5/04	8/23/04	INO[8%]	$2,250.00	$4,500.00
351	1.12.1.1.2	Technical Management	50 hrs	5/5/04	8/23/04	INO[8%]	$2,250.00	$4,500.00
352	1.12.1.1.3	Technical Management	50 hrs	5/5/04	8/23/04	UdeM[8%]	$0.00	$2,500.00
353	**1.12.1.2**	**Scientific Requirements**	**80 hrs**	**5/5/04**	**5/11/04**		**$0.00**	**$4,000.00**
354	1.12.1.2.1	Science Case input (UdeM)	40 hrs	5/5/04	5/11/04	UdeM	$0.00	$2,000.00
355	1.12.1.2.2	OCDD input	40 hrs	5/5/04	5/11/04	UdeM	$0.00	$2,000.00
356	1.12.1.3	Dual-Beam Imaging	90 hrs	5/12/04	5/27/04	UdeM	$0.00	$4,500.00
357	**1.12.1.4**	**4-lambda Multi-colour Detector Assembly (MCDA)**	**935 hrs**	**5/5/04**	**9/2/04**		**$22,174.00**	**$66,750.00**
358	**1.12.1.4.1**	**System Requirements (UdeM)**	**120 hrs**	**5/5/04**	**6/14/04**		**$2,700.00**	**$8,400.00**
363	**1.12.1.4.2**	**Preliminary System Design (UdeM-INO)**	**115 hrs**	**6/14/04**	**7/5/04**		**$4,050.00**	**$9,350.00**
370	1.12.1.4.3	ROM cost estimate (INO)	40 hrs	7/5/04	7/8/04	INO,UdeM	$1,024.00	$3,200.00
371	1.12.1.4.4	Performance Simulation (UdeM)	100 hrs	5/5/04	5/21/04	UdeM	$0.00	$5,000.00
372	**1.12.1.4.5**	**Performance simulations (UdeM)**	**200 hrs**	**5/21/04**	**6/25/04**		**$0.00**	**$10,000.00**
375	**1.12.1.4.6**	**Data Reduction pipeline (UdeM)**	**40 hrs**	**7/5/04**	**7/8/04**		**$0.00**	**$2,000.00**
378	**1.12.1.4.7**	**Optical Design (INO)**	**230 hrs**	**7/5/04**	**9/2/04**		**$10,350.00**	**$20,700.00**
390	**1.12.1.4.8**	**Optical Coatings & Micro-Optics (INO)**	**90 hrs**	**7/5/04**	**8/4/04**		**$4,050.00**	**$8,100.00**
397	**1.12.2**	**Post down-select**	**925 hrs**	**9/2/04**	**12/21/04**		**$0.00**	**$44,113.00**
398	**1.12.2.1**	**Project General**	**150 hrs**	**9/2/04**	**12/21/04**		**$4,500.00**	**$11,500.00**
399	1.12.2.1.1	Management (project)	50 hrs	9/2/04	12/21/04	INO[8%]	$2,250.00	$4,500.00
400	1.12.2.1.2	Technical Management	50 hrs	9/2/04	12/21/04	INO[8%]	$2,250.00	$4,500.00
401	1.12.2.1.3	Technical Management	50 hrs	9/2/04	12/21/04	UdeM[8%]	$0.00	$2,500.00
402	**1.12.2.2**	**Mechanical Design**	**445 hrs**	**9/2/04**	**11/3/04**		**$14,009.00**	**$34,650.00**
403	**1.12.2.2.1**	**Opto-mechanical Design**	**135 hrs**	**9/2/04**	**9/20/04**		**$4,169.00**	**$10,750.00**
412	**1.12.2.2.2**	**Cryostat Design**	**150 hrs**	**9/20/04**	**10/6/04**		**$2,640.00**	**$9,500.00**
417	1.12.2.2.3	Thermal Enclosure	60 hrs	10/7/04	10/18/04	INO	$2,700.00	$5,400.00
418	1.12.2.2.4	Mechanical Interface (space frame, ISS interface plate)	100 hrs	10/18/04	11/3/04	INO	$4,500.00	$9,000.00
419	**1.12.2.3**	**Electronic Design**	**150 hrs**	**9/2/04**	**9/15/04**		**$2,336.00**	**$9,800.00**
420	**1.12.2.3.1**	**Detector Electronics**	**100 hrs**	**9/2/04**	**9/15/04**		**$2,336.00**	**$7,300.00**
425	**1.12.2.3.2**	**Instrument Control**	**50 hrs**	**9/2/04**	**9/10/04**		**$0.00**	**$2,500.00**
429	**1.12.2.4**	**Instrument Control Software**	**140 hrs**	**9/2/04**	**9/17/04**		**$3,392.00**	**$10,600.00**
430	1.12.2.4.1	Software requirement (input-output)	30 hrs	9/2/04	9/6/04	INO,UdeM	$736.00	$2,300.00
431	1.12.2.4.2	Component controller software	40 hrs	9/6/04	9/10/04	INO,UdeM	$1,024.00	$3,200.00
432	1.12.2.4.3	Temperature controler software	30 hrs	9/10/04	9/14/04	INO,UdeM	$736.00	$2,300.00
433	1.12.2.4.4	Instrument controler software	40 hrs	9/14/04	9/17/04	INO,UdeM	$896.00	$2,800.00
434	1.12.2.5	Alignment Plan	40 hrs	9/2/04	9/8/04	INO	$1,800.00	$3,600.00
435	1.12.2.6	Science Instrument Down-Select	0 hrs	9/2/04	9/2/04		($26,037.00)	($26,037.00)
436								



ExAOC Conceptual Design Work Breakdown Structure

ID	WBS	Task Name	Work	Start	Finish	Resource Names	Gemini Cost	TOTAL Cost
437	**1.13**	**Overall Mechanical/Electrical Architecture**	**430 hrs**	**5/5/04**	**12/1/04**		**$0.00**	**$23,973.50**
438	1.13.1	initial mechanical functionality matrix	40 hrs	5/5/04	5/18/04	Lockwood[50%]	$0.00	$2,128.40
439	1.13.2	initial layout	60 hrs	5/19/04	6/2/04	Wallace[70%]	$0.00	$3,558.00
440	1.13.3	bench	80 hrs	11/3/04	11/23/04	Lockwood[70%]	$0.00	$4,256.80
441	1.13.4	enclosure	30 hrs	11/23/04	12/1/04	Lockwood[70%]	$0.00	$1,596.30
442	1.13.5	motion control	200 hrs	5/19/04	7/7/04	Alcott[70%]	$0.00	$11,248.00
443	1.13.6	electronics enclosure	20 hrs	7/7/04	7/13/04	Wallace[70%]	$0.00	$1,186.00
444								
445	**1.14**	**Integrated Model Study**	**306 hrs**	**5/5/04**	**9/7/04**		**$0.00**	**$30,735.00**
449								
450	**1.15**	**Project Management**	**1,147 hrs**	**5/3/04**	**12/31/04**		**$21,205.00**	**$105,530.00**
451	1.15.1	UCSC contract charge	0 hrs	5/3/04	5/3/04		$12,250.00	$12,250.00
452	1.15.2	technical management	420 hrs	5/3/04	12/31/04	Macintosh2[30%]	$0.00	$34,860.00
453	1.15.3	administrative management	560 hrs	5/3/04	12/31/04	Palmer2[40%]	$0.00	$46,480.00
454	**1.15.4**	**Canadian Management**	**132 hrs**	**5/3/04**	**11/26/04**		**$8,955.00**	**$11,940.00**
455	1.15.4.1	Cdn coordination	96 hrs	5/3/04	11/26/04	Murowinski[3%],Ford	$6,446.25	$8,595.00
456	1.15.4.2	SOW and contract development: UdeM and INO	36 hrs	5/3/04	5/12/04	Murowinski[25%],For	$2,508.75	$3,345.00
457	**1.15.5**	**mechanical/electrical management**	**35 hrs**	**5/4/04**	**12/28/04**		**$0.00**	**$0.00**
493								
494	**1.16**	**Documents And Final Instrument Proposal**	**472 hrs**	**5/5/04**	**2/28/05**		**$5,670.00**	**$29,762.48**
495	1.16.1	provide inputs for deliverable documents	0 hrs	5/5/04	12/28/04		$0.00	$0.00
496	1.16.2	technical editing	160 hrs	9/9/04	12/30/04	techEditor[25%]	$0.00	$5,600.00
497	1.16.3	provide draft text for final instrument proposal	0 hrs	5/5/04	12/28/04		$0.00	$0.00
498	1.16.4	merge draft text from collaborators into a single document	0 hrs	12/2/04	12/30/04		$0.00	$0.00
499	1.16.5	provide WBS, schedule, and budget inputs, preliminary	64 hrs	10/25/04	11/1/04	Oppenheimer[20%],V	$0.00	$4,972.08
500	1.16.6	provide WBS, schedule, and budget inputs, preliminary, U	16 hrs	10/25/04	11/1/04	Cowley[20%],Deich[2	$0.00	$562.08
501	1.16.7	provide WBS, schedule, and budget inputs, preliminary, H	24 hrs	10/25/04	11/1/04	Dunn[20%],Murowins	$1,890.00	$2,520.00
502	1.16.8	merge WBS, schedule, and budget inputs, preliminary	0 hrs	11/1/04	11/15/04		$0.00	$0.00
503	1.16.9	provide WBS, schedule, and budget inputs, final	128 hrs	11/18/04	12/2/04	Oppenheimer[20%],V	$0.00	$9,944.16
504	1.16.10	provide WBS, schedule, and budget inputs, final, U	32 hrs	11/18/04	12/2/04	Deich[20%],Cowley[2	$0.00	$1,124.16
505	1.16.11	provide WBS, schedule, and budget inputs, final, H	48 hrs	11/18/04	12/2/04	Veran[20%],Murowin	$3,780.00	$5,040.00
506	1.16.12	merge WBS, schedule, and budget inputs, final	0 hrs	12/2/04	12/30/04		$0.00	$0.00
507	1.16.13	provide project plan for final instrument	0 hrs	12/2/04	12/29/04		$0.00	$0.00
508	1.16.14	provide budget for final instrument	0 hrs	12/2/04	12/29/04		$0.00	$0.00
509	1.16.15	provide management plan for final instrument	0 hrs	12/2/04	12/29/04		$0.00	$0.00
510	1.16.16	adjustments as per CoDR	0 hrs	2/1/05	2/28/05		$0.00	$0.00



CURRICULUM VITAE

Bruce Alan Macintosh

Present Positions:	Physicist I Division / Institute of Geophysics and Planetary Physics Lawrence Livermore National Laboratory 7000 East Ave. Livermore, CA 94550 (925)423-8129 bmac@igpp.llnl.gov	1997-Present
	Multi-Location Appointment UC Observatories Laboratory for Adaptive Optics University of California, Santa Cruz 1156 High Street Santa Cruz, CA 95064	2003-Present
	Member, NSF Center for Adaptive Optics	

Past positions:	Postdoctoral Researcher Institute of Geophysics and Planetary Physics Lawrence Livermore National Laboratory	1994-1997
Education:	Ph.D., Astronomy, 1994 University of California, Los Angeles B.Sc., Physics, 1988 Trinity College, University of Toronto, Ontario, Canada	

Research Interests:

- Direct detection of extrasolar planets
- Development of next-generation “extreme” high-contrast adaptive optics systems
- Astronomical adaptive optics: design, performance characterization, and observational techniques

Major projects, accomplishments, and awards

- Led Center for Adaptive Optics “Extreme Adaptive Optics Planet Imager” design study
- PI on Center for Adaptive Optics Keck AO performance characterization project that raised H-band Strehl ratio from 0.25 to 0.4
- Committees: NSF AO Development Program roadmap committee; TPF technology review board; Keck Observatory AO Working Group

RECENT/RELEVANT PUBLICATIONS

Macintosh, B., et al., “Extreme Adaptive Optics Planet Imager: XAOPI”, 2004 *Proc. SPIE* **5170**, 272

Duchene, G., McCabe, C., Ghez, A., and Macintosh, B., “A multi-wavelength scattered light analysis of the dust grain population in the GG Tau circumbinary ring”, 2004 *Ap.J.* in press

Dekany, R, Stapelfeldt, K., Traub, W., Macintosh, B., Woolf, N., Colavita, M., Trauger, J., and Ftaclas, C., 2004 *PASP* submitted

Poyneer, L, and Macintosh, B, “Spatially-filtered wavefront sensor for high-order adaptive optics”, 2004 *Optics Letters* in press

Macintosh, B., Becklin, E., Kaisler, D., Konopacky, Q., and Zuckerman, B., “Deep adaptive optics searches for planets in the dust of Epsilon Eridani and Vega”, 2003 *Ap.J.* **594**, 538

David Palmer

9/02 – present Lawrence Livermore National Laboratory, Livermore, CA

- Developed an upgrade to the Adaptive Optics Real-time Control Computer for the Lick Observatory.

7/97 – 9/02 Andros Incorporated, Richmond, CA

- Managed a multi-year, multi-million-dollar, inter-disciplinary project to develop an IR anesthesia gas analyzer to be sold into the hospital operating room market. Also served as lead software engineer for this project.
- Managed and served as software engineer for 2 smaller projects.

8/85 - 8/90 GTE Government Systems Corporation, Mountain View, CA

- Served as the Program Technical Manager and software engineer for a signal processing system.
- Served as the administrative manager for a section of software engineers.
- Developed most of the software for an energy detection subsystem.
- Developed the software for a data processing subsystem.
- Served as a member of the core team for 2 proposals.

8/83 - 8/85 Zendex Corporation, Dublin, CA

- Configured, supported, and provided device drivers for several operating systems.
- Managed a small software department.

10/80 - 6/83 Perkin-Elmer Corporation, Wilton, CT

- Developed several parts of a large program that controlled a projection mask aligner used in the exposure phases of integrated circuit chip production.

Education:

- Bachelors Degree in Computer Science, May 1980, State University of New York, College at Oswego

CURRICULUM VITAE

James Richard Graham

Present Positions: Professor of Astronomy 1992-present
601 Campbell Hall
University of California, Berkeley CA 94720-3411
(510) 642-8283
jrg@berkeley.edu

Member, NSF Center for Adaptive Optics

Past positions: Research Fellow, California Institute of Technology 1986-1991
Pasadena, CA

Education: Ph.D., 1985
Imperial College, University of London
B.Sc., Physics, 1981
Imperial College, University of London

Research Interests:

- Instrumentation for large telescopes
- Astronomical adaptive optics
- Development of next-generation "extreme" high-contrast adaptive optics systems

Awards:

- Packard Fellow, Sloan Fellow, Dudley Observatory Awardee

RECENT/RELEVANT PUBLICATIONS

Perrin, M. D., Graham, J. R., Kalas, P., Lloyd, J. P., Max, C. E., Gavel, D. T., Pennington, D. M. Gates, E. L. "Laser Guide Star Adaptive Optics Imaging Polarimetry of Herbig Ae/Be Stars" 2004, *Science*, 303, 1345

Macintosh, B., et al., "Extreme Adaptive Optics Planet Imager: XAOPI", 2004, *Proc. SPIE,* **5170**, 272

Figer, D. F., Gilmore, D., Kim, S. S., Morris, M., Becklin, E. E., McLean, I. S., Gilbert, A. M., Graham, J. R., Larkin, J. E., Levenson, N. A., Teplitz, H. I. "High-Precision Stellar Radial Velocities in the Galactic Center", 2003, ApJ, 599, 1139

Perrin, M. D., Sivaramakrishnan, A., Makidon, R., Oppenheimer, B. R. & Graham, J. R. "The Structure of High Strehl Ratio Point-Spread Functions" 2003, ApJ, 596, 702

McCrady, N. A., Gilbert, A. M., & Graham, J. R., "Kinematic Masses of Super Star Clusters in M82 from High-Resolution Near-Infrared Spectroscopy" 2003, ApJ, 596, 240

Lloyd, J. P., Gavel, D. T., Graham, J. R., Hodge, P. E., Sivaramakrishnan, A., Voit, G. M., "Four-quadrant phase mask coronagraph: analytical calculation and pupil geometry" 2003, Proc. SPIE, 4860, 171

Brian Jeffrey Bauman

Present Positions:	Optical Instrumentation Engineer I Division, Physics and Technology Directorate Lawrence Livermore National Laboratory 7000 East Ave. Livermore, CA 94550 (925)4236592 bauman3@.llnl.gov	1998-present
	Multi-Location Appointment UC Observatories Laboratory for Adaptive Optics University of California, Santa Cruz 1156 High Street Santa Cruz, CA 95064	
	Member, NSF Center for Adaptive Optics	

| Past positions: | Optical Engineer
Atomic Vapor Laser Isotope Separation Program
Lawrence Livermore National Laboratory | 1995-1998 |
| Education: | Ph.D., Optical Sciences, 2004
University of Arizona
M.S., Optical Sciences, 1991
University of Arizona
B.S., Engineering Physics, 1986
University of California, San Diego | |

Research Interests:

- Development of adaptive optics systems for extremely large telescopes
- Development of next-generation "extreme" high-contrast adaptive optics systems
- Astronomical adaptive optics instrumentation: optical design, integration, and testing

Major projects, accomplishments, and awards

- PI on Center for Adaptive Optics project, "Pyramid Wavefront Sensors and Layer-Oriented Adaptive Optics"
- Thirty Meter Telescope adaptive optics
- California Extremely Large Telescope adaptive optics
- Optical Engineer for Lick Observatory Adaptive Optics System
- "R&D 100" Award from *R&D Magazine* for "MEMS-based Adaptive Optics Phoropter"

RECENT/RELEVANT PUBLICATIONS

Bauman, B., "Optical Design for Extremely Large Telescope Adaptive Optics Systems", Ph.D. dissertation, 2003.

Nelson, J., et al., "California Extremely Large Telescope: Conceptual Design for a Thirty-Meter Telescope", CELT Report #34, University of California/California Institute of Technology, June 2002.

Bauman B., Gavel D., "Astronomy applications of adaptive optics at Lawrence Livermore National Laboratory", SPIE Proceedings, vol.5001, pp.41-9, 2003.

Gavel, D.T., C. E. Max, S. S. Olivier, B. J. Bauman, D.M. Pennington, B. A. Macintosh, J. Patience, C. G. Brown, P. M. Danforth, R. L. Hurd, E. L. Gates, Scott Severson, J. P. Lloyd, "Recent science and engineering results with the laser guidestar adaptive optic system at Lick Observatory", SPIE Proceedings, vol. 4839, 2002.

CURRICULUM VITAE

René Doyon

Present Position: Physicist/astronomer (LAE group leader)
Laboratoire d'Astrophysique Expérimentale (LAE)
Département de Physique
Université de Montréal
C.P. 6128 Succ. Centre-ville
Montréal, Qc, H3C 3J7, Canada.
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doyon@astro.umontreal.ca

Member: JWST NIRCam science team, JWST FGS-TF science team

Past positions:

Past positions:	Postdoctoral Researcher, Université de Montréal	1991-1993
	Research associate, Université de Montréal	1994-1998

Education: Ph.D., Astrophysiscs, 1991
Imperial College of Science and Technology and Medicine, London (UK)
M.Sc., Physics, 1987; BSc Physics, 1985
Université de Montréal, Québec, Canada.

Research Interests:

- Infrared instrumentation, high-contrast imaging techniques, coronagraphy
- Brown dwarfs, sub-stellar IMF, search for free floating planets
- Imaging detection of extrasolar planets

Major projects, accomplishments, and awards

- Leader of followings IR instrumentation projects on CFHT:
  - **KIR** (AOB IR camera; 1997), **CFHT-IR** (facility IR camera; 2001), optics package for **WIRCAM** (wide field IR camera; 2004), **TRIDENT** (high-contrast imager; 2001), **SIMON** (cryogenic IR MOS; 2003)
  - **CPAPIR**: wide-field 2kx2k IR camera for the 1.6m Observatoire du Mont Mégantic (2004)

RECENT/RELEVANT PUBLICATIONS

Doyon, R., Lafrenière, D., Marois, C., Racine, R. Nadeau, D. 2004, " Detecting and characterizing exoplanets with multi-color detector assemblies", 2nd Baskaskog meeting on Extremely Large Telescope, Proc. SPIE, in press.

Marois, C., Doyon, R., Nadeau, D., Racine, R., Riopel, M., and Vallee, P. 2003, "TRIDENT: an infrared camera optimized for the detection of methanated substellar companions of nearby stars",High-Contrast Imaging for Exo-Planet Detection. Edited by Alfred B. Schultz. Proceedings of the SPIE, Volume 4860,130-137.

Marois, C., Doyon, R., Racine, R., and Nadeau, D. 2000, "Efficient Speckle Noise Attenuation in Faint Companion Imaging", PASP, 112, 91.

Donald T. Gavel
UCO/Lick Observatory
University of California, Santa Cruz
1156 High Street, Santa Cruz, CA 95064
(831)-459-5464 gavel@ucolick.gov

EDUCATION

Ph. D. Electrical Engineering, University of California, Davis, 1988.
M. S. Electrical Engineering, Stanford University, 1976.
B. S. Electrical Engineering, M.I.T., 1975.

RESEARCH EXPERIENCE

Director, UCO/Lick Observatory Laboratory for Adaptive Optics, 2003-.

Project Scientist, Lawrence Livermore National Laboratory (LLNL) Astronomical Adaptive Optics Program, 1998-2003.

Project Scientist, Ophthalmic Imaging Instruments for the Eye, DOE Biomedical Engineering Grant, FY 2002-2003.

Co-Investigator: Laser Guided Adaptive Optics for Astronomy, LLNL Director's Initiative Project, FY 1993-1997.

RESEARCH INTERESTS

Adaptive Optics in Astronomical Instrumentation, High Resolution Astronomy, Application of Adaptive Optics to Vision Science and Ophthalmology

SELECTED PUBLICATIONS

Perrin, M.D., Graham, J.R., Kalas, P., Lloyd, J.P., Max, C.E., Gavel, D.T., Pennington, D.M., Gates, E.L., *Laser Guide Star Adaptive Optics Imaging Polarimetry of Herbig Ae/Be Stars*, **Science**, 27 February 2004; 303: 1345-1348.

Poyneer, L.A., Gavel, D.T., and Brase, J.M., *Fast wavefront reconstruction in large adaptive optics systems using the Fourier transform*, **Journal Of The Optical Society Of America A**, V 19, n 10, Nov., 2002, 2100-2111.

Gavel, D.T., *Technology challenges to adaptive optics on extremely large telescopes*, **Beyond Conventional Adaptive Optics**, proceedings of the conference held in Venice, May 7-10, 2001, Eds. Roberto Ragazzoni, Norbert Hubin and Simone Esposito, European Southern Observatory, 2001.

Wizinowich, P., D. S. Acton,, C. Shelton,, P. Stomski, , J. Gathright,, K. Ho, W. Lupton, K. Tsubota,, O. Lai, C. Max, J. Brase, J. An, K Avicola, S. Olivier, D. Gavel, B. Macintosh, A. Ghez, J Larkin, *First Light Adaptive Optics Images from the Keck II Telescope: A New Era of High Angular Resolution Imagery*, **The Publications of the Astronomical Society of the Pacific**, V. 112, n. 769, March 2000, 315-319.

S.G. Gibbard, B. Macintosh, D. Gavel, C.E. Max, I. de Pater, A.M. Ghez, E.F. Young, and C.P. McKay, *Titan: High-resolution speckle images from the Keck telescope*, **Icarus**, V. 139, June, 1999, 189-201.

C.E. Max, S.S. Olivier, H.W. Friedman, J. An, K. Avicola, B.V. Beeman, H.D. Bissinger, J.M. Brase, G.V. Erbert, D.T. Gavel, K. Kanz, B. Macintosh, K.P. Neeb, K.E. Waltjen, M.C. Liu, and J. Patience, *Image*

improvement from a sodium-layer laser guide star adaptive optics system, **Science**, 277, pp 1649-1652, September 12, 1997.

D.T. Gavel, C. E. Max, E. J. Johansson, B. Sherwood, M. Liu, B. Bradford, *Observations of Comet P/Shoemaker-Levy 9 Impact on Jupiter from Lick Observatory Using a High Resolution Speckle Imaging Camera*, **IAU Symposium 156**, Space Telescope Science Institute, Baltimore, MD, May 9-12, 1995.

D.T. Gavel, J. R. Morris, and R. G. Vernon, *Systematic Design and Analysis of Laser-Guide-Star Adaptive-Optics Systems for Large Telescopes*, **Journal of the Optical Society of America A**, Vol. 11, No. 2, February, 1994, 914-924.

D. T. Gavel and S. S. Olivier, *Simulation and Analysis of Laser Guide Star Adaptive Optics Systems for the Eight to Ten Meter Class Telescopes*, **SPIE** 1994 Symposium on Astronomical Telescopes and Instrumentation for the 21st Century, Kona, HI, 13-18 March, 1994.

S. S. Olivier, C. E. Max, D. T. Gavel, and J. M. Brase, *Tip-Tilt Compensation: Resolution Limits for Ground-Based Telescopes Using Laser Guide Star Adaptive Optics*, **The Astrophysical Journal**, V. 407, April 10, 1993, 428-439.

Joseph J. Green

Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Drive, Pasadena CA 91109
(818) 354-8403 • Joseph.J.Green@jpl.nasa.gov

Education

The University of Arizona Tucson, AZ

- Ph.D. in Electrical Engineering (minor in Optical Science), *May 2000*
- Master of Science in Electrical Engineering (minor in Optical Science), *December 1997*

The University of Michigan Dearborn, MI

- Bachelor of Science in Electrical Engineering, *December 1994*
- Bachelor of Science in Engineering Mathematics, *December 1994*

Professional Experience

Jet Propulsion Laboratory, Caltech Pasadena, CA *May 2000 – Present*

Senior Member of Technical Staff

- Terrestrial Planet Finder (TPF) Project
  - Developed and implemented image based wavefront sensing methods for the TPF high contrast imaging testbed (HCIT) that demonstrated better than $\lambda/10000$ repeatability and $\lambda/5000$ wavefront control
  - Conducted coronagraph sensitivity studies and developed error models that are currently used by the HCIT and the TPF design team.
- James Webb Space Telescope (JWST) Project
  - Developed wavefront sensing and control algorithms for segmented telescopes.
  - Developed methods of mapping science requirements into system constraints
- Space Infrared Telescope Facility (SIRTF) Project
  - Conducted independent analysis of SIRFT ground testing imagery. Results used to cross-validate the SIRTF efforts to determine the best focus position of the secondary mirror.
  - Analyzed on-orbit calibration data that verified that SIRTF has achieved its Strehl requirements.

The University of Arizona Tucson, AZ *Aug. 1995 – May 2000*

Department of Electrical & Computer Engineering

- Graduate Research Associate
  - Conducted research in the areas of image processing, information theory and pattern recognition.
- Graduate Teaching Assistant

Selected Publications

1. J. J. Green, et. al., “Demonstration of extreme wavefront sensing performance on the TPF high contrast imaging testbed,” Proc. SPIE, vol 5170, (San Diego 2003)
2. J. J. Green, et. al., "Extreme Wave Front Sensing Accuracy for the Eclipse Coronagraphic Space Telescope," Proc. SPIE, vol. 4860 (Waikoloa 2002).
3. J. J. Green, et. al., “Interferometric validation of image-based wave front sensing for NGST,” Proc. SPIE, vol. 4860 (Waikoloa 2002).
4. J. J. Green, “Multiframe Restoration Methods for Image Synthesis and Recovery,” Doctoral Dissertation, The University of Arizona, Tucson, AZ, May 2000.
5. J. J. Green and B. R. Hunt, “Improved Restoration of Space Object Imagery,” J. Opt. Soc. Am. A, vol. 16, no. 12, pp. 2859-65, 1999.
6. (Invited) J. J. Green and B. R. Hunt, “Super-Resolution of Atmospheric Degraded Imagery,” in 1999 International Symposium on Optical Science, Engineering, and Instrumentation, Denver, CO, 1999.

CURRICULUM VITAE
James Edwin Larkin

Present Positions: Associate Professor
Physics and Astronomy Department
University of California, Los Angeles
8967 Math Sciences
Los Angeles, CA 90095-1562
(310)825-9470
larkin@astro.ucla.edu

Member, NASA ORIGINS subcommittee (April 2001 – present)
Member, NSF Center for Adaptive Optics

Past positions: McCormick PostPostdoctoral Fellow 1995-1997
University of Chicago

Education: Ph.D., Physics, 1996
Caltech
B.Sc., Physics and Mathematics, 1990
Calif. State Univ., Hayward

Research Interests:

- Infrared instrumentation for adaptive optics systems
- Galaxy Evolution, especially with adaptive optics

Major projects, accomplishments, and awards

- Currently PI for the OSIRIS integral field spectrograph for the Keck AO system.
- Currently Co-I for the KIRMOS infrared multi-object spectrograph for Keck.
- Co-I on the NIRC2 infrared camera and spectrograph for the Keck AO system.
- Alfred P. Sloan research fellow from 2000-2002.
- Co-I on the NIRSPEC infrared spectrograph for Keck
- PI for the KCAM infrared camera, which was the first light camera for the Keck AO system..
- Co-PI for the CATS legacy project – Observing Galaxy Evolution with AO (CfAO project).

RECENT/RELEVANT PUBLICATIONS
From 82 Publications (39 Refereed)

Larkin, James E.. et al., "OSIRIS: Infrared Integral Field Spectrograph for the Keck Adaptive Optics System", 2003 *Proc. SPIE* **4841**, 1600.

Glassman, T. M., Larkin, J. E., & Lafreniere, D., "Morphological Evolution of Distant Galaxies from Adaptive Optics Imaging", 2002, ApJ, 581, 865.

Larkin, J.E. et al., "Exploring the Structure of Distant Galaxies with Adaptive Optics on the Keck II Telescope", 2000, PASP, 112, 1526.

Professor Ian S. McLean
Dept. Physics & Astronomy, UCLA

Positions:

1967 – 1971	B.Sc. (Hons) Physics & Astronomy, University of Glasgow, Scotland
1971 – 1974	PhD Astronomy, University of Glasgow
1974 – 1976	SERC post-doctoral research fellow & Visiting Astronomer, Lowell Observatory, Flagstaff, Arizona
1976 – 1979	Research Fellow Steward Observatory, University of Arizona
1980 – 1989	Principal Scientific Officer, Royal Observatory Edinburgh, Head of IR Detector Development & senior management team, UK Infrared Telescope, Hawaii
1989 –	Professor, Dept. Physics & Astronomy, UCLA Director, Infrared Imaging Detector Lab
2001 –	Associate Director, University of California Observatories
2004 –	Co-chairman of the Keck Science Steering Committee

Areas of Research:
Infrared instrumentation & infrared detectors; IR spectroscopy & imaging; brown dwarfs; star forming regions; galactic center; high-z galaxies; polarization techniques.

Major Achievements:
Depolarization (McLean effect) of the H-alpha/H-beta lines in Be stars (1974)
Orbital inclination from phase-locked polarization in close (X-ray) binaries (1976)
Pioneered on-chip charge-shifting (shuffling) for differential measurements (1981)
Developed first CCD imaging spectro-polarimeter (1983)
PI for IRCAM, the first infrared camera on UKIRT to use 62 x 68 InSb array (1986)
PI for UCLA twin-channel IR camera for Lick Observatory (1993)
PI for NIRSPEC, a near-IR spectrometer for the Keck Observatory (1999)
The Keck NIRSPEC Brown Dwarf Spectroscopic Survey (2003)
PI for FLITECAM, a wide-field IR camera for SOFIA (2004)

Previous Graduate Students (and current positions):
Mark McCaughrean (Bonn), John Rayner (UH/IRTF), Suzanne Casement (TRW), Don Figer (STScI), Harry Teplitz (SSC), Sam Larson (Hughes); Amanda Mainzer (JPL)

Publications: Over 250 publications including:
1. *Infrared Astronomy with Arrays: the next generation* 1994, Kluwer Academic Publishers, Netherlands
2. *Electronic Imaging in Astronomy: detectors and instrumentation* 1997, Praxis Publishing, UK
3. "Design and development of NIRSPEC: a near-infrared echelle spectrograph for the Keck II telescope" 1998, Proc. SPIE Vol. 3354, p. 566-578, Infrared Astronomical Instrumentation, Albert M. Fowler; Ed.
4. McLean, I.S. et al. 2003, ApJ 596, 561: The NIRSPEC Brown Dwarf Spectroscopic Survey. I Low-Resolution Near-Infrared Spectra

CURRICULUM VITAE

Rick Murowinski

Present Positions: Deputy-Leader
Astronomical Technology Research Group-Victoria
Herzberg Institute of Astrophysics
5071 W. Saanich Rd
Victoria B.C.
(250) 363 0057
Richard.Murowinski@nrc.ca

Education: B.Eng – Engineering Physics - 1978
Royal Military College of Canada,
Kingston, Ontario

Professional Affiliation:
Member of Ontario Association of Professional Engineers,
Member of Institute for Electrical and Electronic Engineers,
Member of Canadian Astronomical Society

Research Interests:

- Detectors: UV photon counting, CCDs and NIR infrared arrays.
- Effects of energetic particle radiation on solid state detectors.

Major projects, accomplishments, and awards

- System Engineer and Canadian Project Manager for the GMOSs
- National Research Council's Outstanding Achievement Award, 2002
- Currently System Engineer for JWST's Fine Guidance Sensor instrument

RECENT/RELEVANT PUBLICATIONS

Murowinski, R. et al, "Gemini-North Multiobject Spectrograph Integration, Test and Characterization", 2004 *PASP* submitted.

Hook, I. et al., "The Gemini-North Multiobject Spectrograph (GMOS): Imaging, long-slit and mulit-object spectroscopic modes" , 2004 *PASP* in press.

Abraham, R. et al, "The Gemini Deep Deep Survey: I. Introduction to the Survey, Catalogs and Composite Spectra" 2004 *AJ* in press.

Savaglio, S. et al., The Gemini Deep Deep Survey: II. Metals in Star-Forming Galaxies at Redshift 1.3<z<2", *Astrophys.J*. 602 (2004) 51-65

BEN R. OPPENHEIMER
RESEARCH FELLOW
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AMERICAN MUSEUM OF NATURAL HISTORY
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EDUCATION

1999	Ph.D., Astronomy, California Institute of Technology
1994	B.A., Physics, Columbia College, Columbia University

FELLOWSHIPS, AWARDS, HONORS

2003	Carter Memorial Lecturer, Carter Observatory, Wellington, New Zealand
2002-present	Kalbfleisch Research Fellow, American Museum of Natural History
2002	National Academy of Sciences, Beckman Frontiers of Science Participant
1999-2002	Hubble Postdoctoral Research Fellow, AMNH, UC-Berkeley
2000	Douglass Scholar, Steward Observatory, University of Arizona, Tucson
1994-1997	National Science Foundation Graduate Research Fellow
1990-1994	I.I. Rabi Science Scholar, Columbia University

EMPLOYMENT

2002-present	Research Fellow, American Museum of Natural History
2000-2001	Hubble Research Fellow, University of California-Berkeley
1994-1998	Graduate Research Fellow, California Institute of Technology, with Kulkarni
1993-1994	Instructor, Barnard College Physics Department, History of Physics
1993-1995	Instructor, Columbia University Summer Program for High School Students

SELECTED LIST OF PUBLICATIONS

1. "Imaging Exoplanets: The Role of Small Telescopes" by B. R. Oppenheimer, A. Sivaramakrishnan and R. B. Makidon in *The Future of Small Telescopes*, Terry Oswalt, ed., Vol. III, p. 155 (Dordrecht, The Netherlands: Kluwer Academic Publishers; 2003).
2. "Coronagraphic Survey for Companions of Stars within 8pc" by B. R. Oppenheimer, D. A. Golimowski, S. R. Kulkarni, K. Matthews, T. Nakajima, M. Creech-Eakman, and S. T. Durrance, *The Astronomical Journal,* Vol. 121, p. 2189 (2001 April).
3. "The Spectrum of the Brown Dwarf Gliese 229B" by B. R. Oppenheimer, S. R. Kulkarni, K. Matthews and M. H. van Kerkwijk, *The Astrophysical Journal,* Vol. 502, p. 932, (1998 August 1).
4. "Near IR spectrum of the cool brown dwarf GL 229B" by B. R. Oppenheimer, S. R. Kulkarni, K. Matthews, T. Nakajima, *Science*, Vol. 270, 1478 (1995).
5. "Discovery of a cool brown dwarf" by T. Nakajima, B. R. Oppenheimer, S. R. Kulkarni, D. A. Golimowski, S. T. Durrance, K. Matthews, *Nature*, Vol. 378, p. 463 (1995).

Lisa A. Poyneer

Present Position:

Engineer, Adaptive Optics and Signal Processing
Lawrence Livermore National Lab
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Livermore, CA 94551
925 423 3360 poyneer1@llnl.gov

Education:

PhD candidate, Electrical and Computer Engineering
UC Davis, joint with LLNL
BA in Modern History, upper second class honors (2001)
Worcester College, Oxford University, England
M. Eng Electrical Engineering and Computer Science, GPA 5.0/5.0 (1999)
SB Computer Science and Engineering, GPA 5.0/5.0 (1998)
Massachusetts Institute of Technology

Research Interests:

Signal Processing for Adaptive Optics, including wave-front sensing, wave-front reconstruction and control.

Honors:

Rhodes Scholar, 1999
Henry Ford II Scholar, 1998: highest level of academic excellence for a senior in MIT's School of Engineering.
Association of MIT Alumnae Award, 1998: highest level of academic and professional excellence for a female undergraduate at MIT.

Recent/Relevant Publications

L. A. Poyneer and B. Macintosh, "Spatially filtered wave-front sensor for high-order adaptive optics", J. Opt. Soc. Am. (A), (in press May 2004).

L. A. Poyneer, "Scene-based Shack-Hartmann wave-front sensing: analysis and simulation", Applied Optics IP **42**, pp 5807-15, (Oct 2003).

L. A. Poyneer, M. Troy, B. Macintosh and D. Gavel, "Experimental validation of Fourier transform wave-front reconstruction at the Palomar Observatory", Optics Letters **28** 798-800, (May 2003).

L. A. Poyneer, "Advanced techniques for Fourier transform wavefront reconstruction", SPIE **4839** Adaptive Optical System Technologies II, pp 1023-1033, (2002).

L. A. Poyneer, D. T. Gavel and J. M. Brase, "Fast wavefront reconstruction in large adaptive optics systems with use of the Fourier transform", J. Opt. Soc. Am. (A), **19,** pp 2100-11, (Oct 2002).

Stuart B. Shaklan

Address: Jet Propulsion Laboratory (JPL), 4800 Oak Grove Dr., M.S. 306-388, Pasadena, CA 91109
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E-mail: shaklan@huey.jpl.nasa.gov

Professional Experience

Architect, Terrestrial Planet Finder Coronagraph, JPL	2002-present
Instrument Scientist, Space Interferometry Mission , JPL)	2000-present
Technical Group Supervisor, Interferometer Optics and Metrology Group, JPL	1999-present
Principal Engineer, JPL Technical Staff	1999-present
JPL Technical Staff, Jet Propulsion Laboratory	1991-1999
National Science Foundation Long Term Visiting Scholar at Foreign Center of Excellence, University of Limoges, France	1989-1990

Education

Ph.D. in Optics, University of Arizona, Tucson AZ	1989
B.S. in Physics and Astronomy (with honors), U. Arizona, Tucson AZ	1985

Recent Publications

"Optimizing Coronagraph Designs to Minimize the Sensitivity to Low-Order Optical Aberrations" J. J. Green and S.B. Shaklan, Proc. SPIE 2003 (in press).

"Extreme Wave Front Sensing Accuracy for the Eclipse Coronagraphic Telescope" J. J. Green, D.C. Redding, S.B. Shaklan, and S. A. Basinger, Proc. SPIE vol 4860 (2003).

"A Scheme for On-Orbit Calibration of the Space Interferometry Mission Based on Spacecraft Maneuvering" A. Papalexandris, M.H. Milman, and S. B. Shaklan, PASP 115, 1236 (2003).

"Residual wavefront phase estimation in the Lyot plane for the eclipse coronagraphic telescope" S.B. Shaklan, D. Moody, J.J. Green, Proc SPIE vol 4860 (2003).

"Astrometric Detection of Extra-Solar Planets: Results of a Feasibility Study with the Palomar 5-m Telescope" S. Pravdo and S. Shaklan, Ap. J. **465**, 264 (1996)

"Overview of SIM External Calibration" S.B. Shaklan et al, Proc. SPIE vol 4852 (2003).

"Stellar Planet Survey – STEPS' S.H. Pravdo and S.B. Shaklan, Scientific Frontiers in Research on Extrasolar Planets, ASP Conference Series, Vol 294, 107 (2003)

Currently Funded Proposals:
"A New Approach to Micro-arcsecond Astrometry with SIM Allowing Early Mission Narrow-Angle Measurments of Compelling Astronomical Targets," SIM Instrument Scientist Proposal in response to NASA AO 00S-01 (2001).

Co-Investigator, Stellar Planet Survey, NASA Origins Program (contact Dr J. Boyce, NASA HQ)

Michael Shao

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Phone: 818-354-7834, FAX: 818-393-2412, Email: msaho@huey.jpl.nasa.gov

Positions

Project Scientist, Keck Interferometer Project, Jet Propulsion Laboratory	1997-2004
Project Scientist, SIM Project, Jet Propulsion Laboratory	1997-2004
Director, Interferometry Center of Excellence, Jet Propulsion Laboratory	1996-2004
Spatial Interferometry Group Supervisor, Jet Propulsion Laboratory	1989-1996
Astrophysicist, Smithsonian Astrophysical Observatory	1984-1989
Astrophysicist, Naval Research Laboratory	1981-1984

Education

Ph.D., Astronomy, June 1978	Massachusetts Institute of Technology, Cambridge, MA
B.S., Physics, June 1971	Massachusetts Institute of Technology, Cambridge, MA

Memberships

American Astronomical Society	
Fellow, Optical Society of America	
Co-Chair Space Interferometry Mission Science Working Group (SIMSWSG)	1996-2004
Ex-officio, Keck Interferometer Science Steering Group (KISSG)	1997-2004
Terrestrial Planet Finder Science Working Group	1999-2004

Selected Publications

1. “The Visual Orbit of 64 Piscium”, A. F. Boden, et al. (The PTI Collaboration), *The Astrophysical Journal*, 527, 360 (1999).

2. “The Visual Orbit of ι Pegasi”, A. F. Boden, et al. (The PTI Collaboration), *The Astrophysical Journal*, 515, 356 (1999).

3. “Radii and Effective Temperatures for G, K, and M Giants and Supergiants”, G. T. van Belle, et al. (The PTI Collaboration), *The Astronomical Journal*, 117, 521 (1999).

4. “Visible light Terrestrial Planet Finder: planet detection and spectroscopy by nulling interferometry with a single aperture telescope”, B. M. Levine, et al. *SPIE*, Vol. 4852 (2003).

5. “Interferometer Observations of Subparsec-Scale Infrared Emission in the Nucleus of NGC 4151”, Swain, M., et al. *The Astrophysical Journal*, Vol. 596, Issue 2, pp. L163-L166 (2003).

6. “Observations of DG Tauri with the Keck Interferometer”, M. Colavita, et al. *The Astrophysical Journal,* Vol. 592, Issue 2, pp. L83-L86 (2003).

7. “A distance of 133-137 parsecs to the Pleiades star cluster”, Xiaopei Pan, M. Shao, and S.R. Kulkarni, *Nature,* Vol. 427, pp. 326-328 (January 22, 2004)

CURRICULUM VITAE

Anand Sivaramakrishnan

Present Positions:	JWST Wavefront Sensing and Control Lead Scientist Space Telescope Science Institute 3700 San Martin Drive, Baltimore MD 21218 (410)338-4480 anand@stsci.edu	

Past positions:	Palomar Observatory: AO scientist	1995-1997
	Carnegie Observatories: Instrument scientist	1989-1995
	University of Texas: HST FGS research scientist	1983-1988
Education:	Ph.D., Astronomy, 1984 – University of Texas	
	MA (1978), BA (1974) Physics – Cambridge University	

Research Interests:

- Adaptive optics system development
- Coronagraphic theory & instrumentation
- High-contrast adaptive optics systems
- Speckle reduction techniques

Major projects, accomplishments, and awards

- Theory of AO coronagraphy, including co-founding The Lyot Project
- Theory of high Strehl ratio PSF structure
- Palomar AO system design & development
- Palomar and Las Campanas instrumentation & software development
- Reviewer of ESO VLT Planet Finder, Gemini NICI study phase proposals
- Michelson fellowship mentor (Soummer)

RECENT/RELEVANT PUBLICATIONS

Sivaramakrishnan, A., Soummer, R., Lloyd, J. P., Sivaramakrishnan, A. V., Perrin, M. D., Makidon, R. B., & Oppenheimer, B. R. *Low order aberrations in band-limited Lyot coronagraphs* (2004) ApJ *(submitted)*

Lloyd, J. P. & Sivaramakrishnan, A. *Tip-tilt error in Lyot coronagraphs* (2004) ApJ (Letters) *in press*

Perrin, M. D., Sivaramakrishnan, A., Makidon, R. B., Oppenheimer, B. R., & Graham, J. R. *The structure of high Strehl ratio point-spread functions* (2003), ApJ, **596**, 702

Sivaramakrishnan, A., Lloyd, J. P., Hodge, P. E., & Macintosh, B. A.. *Speckle decorrelation and dynamic range in speckle noise-limited imaging* (2002) ApJ **581**, L59

Sivaramakrishnan, A., Koresko, C. D., Makidon, R. B., Berkefeld, T., & Kuchner, M. J. *Ground-based coronagraphy with high order adaptive optics* (2001) ApJ **552**, 397

Sivaramakrishnan, A. & Oppenheimer, B. R. *Deformable mirror calibration for adaptive optics systems* (1998) Proc. SPIE **3353**, 910

Sivaramakrishnan, A. & Weymann, R. J., & Beletic, J. W. *Measurements of the angular correlation of stellar centroid motion* (1995) AJ **110**, 430

CURRICULUM VITAE

Rémi Soummer

Present Positions: Michelson Postoctoral fellow
Space Telescope Science Institute
3700 San Martin Drive
Baltimore MD 21218
(410)338-4982
soummer@stsci.edu

Past positions: CNRS Postdoctoral Researcher 2002-2003
Laboratoire Universitaire d'Astrophysique de Nice
France

Education: Ph.D., Astronomy, 2002 – Université de Nice, France
Agrégation de l'Université, 1997, France

Research Interests:

- Direct detection of extrasolar planets
- Coronagraphy
- High-contrast adaptive optics systems
- Speckle reduction techniques

Major projects, accomplishments, and awards

- N ew coronagraphic designs: Apodized Pupil Lyot , and Dual Zone Phase Mask
- Conference co-chair "Journées d'imagerie à très haute dynamique" in Nice, France in May 2002 and September 2003

RECENT/RELEVANT PUBLICATIONS

Soummer R., Dohlen K. and Aime C. *Achromatic Dual-Zone Phase Mask Stellar Coronagraph* (2003) A&A (2003) **403,** 369-381

Soummer R., Aime C. and Falloon P. *Stellar coronagraphy with prolate apodized circular apertures* (2003) A&A **397**, 1161-1172

Aime C., Soummer R. and Ferrari A. *Total coronagraphic extinction of rectangular apertures using linear prolate apodizations* (2002) A&A **389**, 334-344

Aime C., Soummer R. and Ferrari A. *Interferometric apodization of rectangular apertures, Application to stellar coronagraphy* (2001) A&A **379**, 697-707

Aime C., Soummer R. and Lopez B. *stellar Coronagraphy with a redundant array of telescopes in space* (2001) A&A, **370**, 680-688

Jean-Pierre Véran
Jean-Pierre.Veran@nrc-cnrc.gc.ca

Education: Ph.D., Electrical Engineering (1997) Ecole Nationale Supérieure des Télécommunications, Paris, France.

Expertise: AO modeling, AO engineering, AO control systems, AO system design and calibration, integration, test and commissioning of AO systems. Astronomical observations with AO. AO data processing. Image deconvolution. PSF estimation. Astrometry and photometry.

Major Projects: Gemini Altair: AO Engineer / Project Scientist. Real-time control system design and optimization; development of diagnostic and calibration procedures; integration, test and commissioning; Gemini South AO preliminary design studies. CFHT PUEO: integration, testing, commissioning and AO loop data processing. Currently member of the TMT AO Working Group and team leader of the AO Group at HIA.

James Kent Wallace
MS 171-113
Phone: 818.393.7066
James.K.Wallace@jpl.nasa.gov

Education

1990 – 1992 Master's Degree in Optics, University of Rochester, Rochester, NY
Thesis: Image Quality Limit for a Reversible System

1984 – 1988 Bachelor's Degree in Physics, Rose-Hulman Institute of Technology, Terre Haute, IN, Minors in Russian and Mathematics

Work Experience

2001 – 3/2002 Optical Engineer, Jet Propulsion Laboratory, Pasadena, CA
Responsible for interferometer design a for visible nulling instrument of a proposed planet finding telescope. Designed and procured optical and mechanical components for the upgrade to the Shack-Hartman wave-front sensor for the Palomar AO system. Continue to experimentally demonstrate deep nulling of IR light for the Terrestrial Planet Finder project.

2001 – 3/2002 Optical Engineer, Holoplex Technologies, Inc.
Designed optical wireless transmission system for high speed data communications for SONET protocol. Constructed low cost erbium doped fiber amplifier (EDFA) for small signal amplification.

Consultant, California Extremely Large Telescope (CELT)
Provided design advice, including optical and mechanical drawings, for the design of a miniature Shack-Hartman wave front sensor.

1992 – 2000 Member of Technical Staff, Jet Propulsion Laboratory, Pasadena, CA
Keck Interferometer
Senior optical engineer for project. Responsible for several subsystems including delay line laser heterodyne metrology system, differential laser heterodyne metrology system, dual-star separation system, interferometer stimulus, baseline monitor. Also served as chief optical engineer for optical nulling interferometer.

Palomar Adaptive Optics System
Designed, assembled and implemented a stimulus for the Palomar Adaptive Optics System. This stimulus consisted of an optical relay to align the pupil and image planes of the telescope and AO system. Stimulus also included a phase-shifting interferometer to align the AO relay.

Palomar Testbed Interferometer
Opto-mechanical engineer responsible for design, procurement, assembly and test of several subsystems of the stellar interferometer.

1991 Masters Co-op Student, Jet Propulsion Laboratory, Pasadena, CA
Tested graphite-composite segmented reflectors with a 10um phase-shifting interferometer in support of the Precision Segmented Reflector program. Modeled the diffraction effects of the submillimeter telescope.

1988 – 1990 Vidicon Product Engineer, MPD, Inc., Owensboro, KY
Engineer responsible for production of 5/8" vidicon imaging tubes.

Awards & Achievements

Group Achievement Award, Palomar Testbed Interferometer, 1997.
Group Achievement Award, Palomar Adaptive Optics System Development Team, May 16, 2000.

Publications

Forbes, G. W. & Wallace, J. K., Can the bounds to system performance in geometrical-optics be attained?, JOSA A 12, 2064-2071, (1995).

Colavita, M. M., Wallace, J. K., Hines, B. E., Gursel, Y., Malbet, F., Palmer, D. L., Pan, X. P., Shao, M., Yu, J. W., Boden, A. F., Dumont, P. J., Koresko, C. D., Kulkarni, S. R., Lane, B. F., Mobley, D. W. & van Belle, G. T., The Palomar testbed interferometer, Ap. J. 510, 505-521, (1999).

Wallace, J. K., Hardy, G. H. & Serabyn, G., Deep and stable interferometric nulling of broadband light with implications for observing planets around nearby stars, Nature, 406, 700-702 (2000).

March 22nd 2004

AURA – Gemini Observatory
950 N. Cherry Ave.
Tucson, AZ 85719
Attention: Contracts Manager; RFP No. N231802

Re: Letter of Support

Dear Sir/Madam
This letter is in support of the proposal for "Conceptual Design Studies for an Extreme Adaptive Optics Coronograph (ExAOC)" being submitted by the University of California Santa Cruz (UCSC) as the prime contractor, with Dr. Bruce Macintosh as the Principal Investigator.

Bruce is a research physicist at the Lawrence Livermore National Laboratory (LLNL) and has been a Principal Investigator funded by the Center for Adaptive Optics (CfAO) at UCSC since its inception in 2000. The CfAO has structured its research into four themes, Education, Extremely Large Telescopes, Extreme Adaptive Optics, and Vision Science. Since 2002, Bruce has led the science efforts in Theme 3 – Extreme Adaptive Optics, the goals of which are to:

- Pursue high contrast science projects related to planetary system formation using existing AO systems with specialized instrumentation (e.g., polarimetry, thermal IR imaging)), and with new ExAO systems when available.
- Complete design phases (conceptual, preliminary, final) of an ExAO system for an 8-10 meter telescope
- Perform demonstration of key techniques (e.g., wavefront sensing and calibration) and technologies (e.g., MEMS deformable mirrors) required to achieve design performance specifications of an ExAO system
- Facilitate completion of programmatic requirements for construction and deployment of an ExAO system an 8-10 meter telescope (e.g., telescope selection, external co-funding, science camera design and external funding)
- Construct, test and deploy an ExAO system on an 8-10 meter telescope

As can be noted, the above goals are closely aligned with those of this proposal.

In addition, in 2003 the Moore Foundation provided UCSC $9.1 million to develop a Laboratory for Adaptive Optics (LAO). The CfAO in conjunction with the LAO has designed AO simulation studies and laboratory experiments that will aid in the development of an Extreme Adaptive Optics coronograph. Bruce will be leading these studies and while continuing to be a researcher at LLNL has accepted a 50 percent time Multi Location Assignment (MLA) within the LAO at UC Santa Cruz. As a research staff member, Bruce will be the Principal Investigator for these activities at UCSC.

The studies being undertaken in this proposal will be overseen by a committee of AO researchers identified and recruited by a steering committee chaired by Scot Olivier, Associate Director of the CfAO. Specific aspects will also be overseen by the CfAO and reviewed during CfAO Retreats and workshops.

I strongly commend this proposal as it is complementary to promising studies that will continue under Bruce's direction within CfAO and LAO and have a high probability of success. Designing and building an ExAO system is high priority for CfAO and the Gemini proposal is a natural outgrowth of this.

Sincerely,

Jerry Nelson
Director Center for Adaptive Optics

March 29, 2004

AURA – Gemini Observatory
950 N. Cherry Avenue
Tucson, AZ 85719

Dear AURA and Gemini Observatory,

I am writing to express UCO/Lick Observatory's full support for the ExAOC proposal being submitted by Dr. Bruce Macintosh. UCO/Lick Observatory is extremely excited by this opportunity to be the principal institution in the development of the world's most advanced adaptive optics system, and it will be the showpiece instrument project for both the NSF Center for Adaptive Optics and our Moore Foundation Laboratory for Adaptive Optics. Although Dr. Macintosh is formally an employee of Lawrence Livermore National Laboratory, he has a Multi Location Appointment with UCO/Lick Observatory and works here 50% of his time, an ideal arrangement for a collaborative Lawrence Livermore National Laboratory/UCO/Lick Observatory project. I believe he is the ideal PI for this project, and I will work to ensure that he has the UCO/Lick Observatory personnel and resources needed to make it succeed. We specifically commit to allocate at least $188,000 of funding from our Laboratory for Adaptive Optics in support of this project as discussed in the attached letter from Dr. Don Gavel.

Sincerely yours,

Joseph S. Miller
Director
UCO/Lick Observatory

JSM/jat

Laboratory for Adaptive Optics
UCO Lick Observatory

March 29, 2004

From: Donald Gavel, Director, Laboratory for Adaptive Optics

To: Andy Flach and Doug Simons, Gemini Observatory Next Generation Instrument Program

Re: Laboratory for Adaptive Optics support for the Extreme AO Coronagraph proposal of Macintosh and Graham

I am writing in strong support of the proposed Extreme Adaptive Optics Coronagraph instrument for the Gemini Observatory. The Laboratory for Adaptive Optics (LAO) is a newly formed entity within the UCO/Lick Observatory on the U.C. Santa Cruz campus that will serve as a research and teaching facility for the development of adaptive optics technology. It is funded for a six year period by the Gordon and Betty Moore foundation and has two primary goals with respect to astronomical adaptive optics: to develop technology for multi-conjugate adaptive optics systems on giant telescopes and to develop technology for high contrast "extreme" adaptive optics for imaging planets around nearby stars.

Since extreme adaptive optics is a fundamental component of our charter, the Laboratory is prepared to commit a significant portion of its resources in the technology development and, if co-supported by a major observatory, the subsequent construction, integration, testing, and commissioning of the EXAOC instrument. The laboratory facilities include the type of precise instrumentation needed to prove the high contrast and scattered light suppression goals are being achieved. The LAO staff consists of some of the foremost experts in adaptive optics and interferometry and in addition has access to the considerable resources of the UCO Lick optics shops. The Lick shops have years of experience fielding instruments on large telescopes, including the Keck 10 meter telescope's ESI and DEIMOS spectrographs.

For the design study phase the LAO will support the PI, Bruce Macintosh, and the project manager, David Palmer, for project management, system definition and leadership tasks through multi-location appointments (MLA) to UC Santa Cruz (approximate cost to LAO: $82k). Additionally, the optomechanical and software design effort at the UCO shops will be supported with LAO funding at a cost of approximately $90k.

Laboratory for Adaptive Optics
UCO Lick Observatory

I look forward to the opportunity to work with the Gemini EXAOC instrument team and to the exciting prospect of building an astronomical instrument with such ground-breaking science possibility.

Donald T. Gavel
Director, Laboratory for Adaptive Optics
UCO/Lick Observatory
UC Santa Cruz
1156 High Street, CfAO Building
Santa Cruz, CA 95064
phone: 831-459-5464
email: gavel@ucolick.org

Thursday, March 25, 2004

Dr. Bruce Macintosh,
NSF Center for Adaptive Optics
University of California Santa Cruz
1156 High Street
Santa Cruz, CA 95064

Dear Bruce,

In this letter, I would like to formally state our intent to collaborate with you in a design study for an Extreme Adaptive Optics Coronagraph (ExAOC) for the Gemini Telescopes. Providing our communities with leading instrumentation for the Gemini telescopes remains one of the primary objectives of the Herzberg Institute of Astrophysics (HIA) and of our group. We are very committed to this collaboration with you, and expect it will be a mutually beneficial and synergistic partnership ultimately enabling new and exciting science at Gemini.

If the proposal which you are preparing in response to AURA's RFP no. N231802 is successful, we intend to participate with you collaboratively in the design study and presentation to Gemini of a concept and a development proposal. It is our intent to join with you in the greater objective of winning the work of collaboratively designing, building and delivering ExAOC to Gemini.

HIA anticipates participating in the conceptual design phase by developing a collaborative agreement with you that specifies:

a) The NSF Center for Adaptive Optics at UC Santa Cruz will be the lead institution on this proposal, and Dr. Macintosh will be the principal investigator
b) That about $US 134,900 be provided to HIA from the initial Gemini award to UCSC, as well as up to about $20,000 for Science Instrument development once that technology decision is made and Science Instrument work distributed among the partners,
c) That about $151,500 of internal resources are to be provided by HIA and its Canadian collaborators,
d) The tasks for which HIA is responsible, on behalf of itself and its Canadian collaborators, are those listed in an attachment to the collaborative agreement,
e) That about $677,600 of internal resources are to be provided by CfAO and its member institutions.
f) The tasks for which CfAO is responsible, on behalf of itself and its US collaborators, are those listed in an attachment to the collaborative agreement,
g) A provision that this collaborative agreement will be extended, under a new agreement, if the concept design is accepted by Gemini.

The agreement will use values determined after the contract has been negotiated with Gemini, and may differ from the above if the scope or distribution of work changes from that being proposed. The initial distribution is outlined in the appendix attached to this letter.

Looking forward to a mutually beneficial and exciting project,

David Crampton
Group Leader,
HIA Astronomy Technology Research Group, Victoria

Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109-8099
(818) 354-4321

JPL

March 29, 2004

Dr. Bruce Macintosh
Center for Adaptive Optics
1156 High St.
Santa Cruz, CA 95064

Dr. Macintosh:

Subject: Extreme Adaptive Optics Coronagraph (ExAOC) Design Studies

The Jet Propulsion Laboratory is pleased to participate as your partner in the design of the ExAOC and is enthusiastic about its potential for scientific studies relating to the detection and characterization of extra-solar planets. We look forward to a productive relationship with you and all the other team members during this project.

We are committed to providing support to the ExAOC design effort under our existing contract with the Center for Adaptive Optics, and we will use our best efforts to become members of the winning team for the development phase of the coronagraph.

If you have any questions regarding JPL's participation on this proposal, please contact J. Kent Wallace at (818) 393-7066.

Sincerely,

Michael Devirian

Michael Devirian, Manager
Origins and Astrophysics Formulation Office

Lawrence Livermore National Laboratory

Physics & Advanced Technologies

March 26, 2004

AURA-Gemini Observatory
950 N. Cherry Avenue
Tucson, AZ 85719

Dear AURA and Gemini Observatory

I am writing to express LLNL’s support for the ExAOC proposal being submitted by Dr. Bruce Macintosh. LLNL has a long history of working on astronomical adaptive optics, and ExAOC is an exciting next step in this area, and we look forward to the opportunity to participate in this project. Dr. Scot Olivier, the Adaptive Optics Group Leader, will work to ensure that Dr. Macintosh has the resources he needs to make the project succeed.

Sincerely yours,

James Brase
I-Division Leader
Physics and Advanced Technologies

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EXAOC Science Instrument
UCLA Statement of Work
Professors James Larkin and Ian McLean

Date: March 18, 2004
Project: EXAOC Conceptual Design
Agency: University of California, Santa Cruz
Budget: $14,855
Period of Performance: May 2004 – Sept 2004

Professors James Larkin and Ian McLean are proposing to become co-Investigators in the EXAOC Instrument for the Gemini Telescopes. Our funds would come as a sub-contract from UCSC which would hold a primary contract with the Associated Universities for Research in Astronomy (AURA) which is the governing body of the Gemini Telescopes and is an international collaboration with funding from multiple agencies including the NSF.

The University of California at Santa Cruz, led by Bruce Macintosh, is proposing to construct an advanced adaptive optics system for the Gemini Telescopes that will directly image Jovian planets around nearby stars. The UCLA Infrared Astrophysics Lab will participate in this program with the intention of constructing the science instrument (a camera or spectrograph) that mounts to the adaptive optics system. At this point, the Investigators are submitting a proposal to participate in the first 5 months of the conceptual design phase. At that point, two instrument concepts will be competed. The winning concept will be further studied during the last half of the conceptual period which ends in November, 2004. At UCLA, we intend to continue as members of the collaboration through the entire study period, but at this time are only requesting funds through the competitive stage of the study.

The primary UCLA activites are centered on trade studies between different instrument configurations and capabilities. This primarily involves Professor James Larkin and graduate student Michael McElwain. Professor Ian McLean will also work on instrument trade studies and on developing a management plan with Professor Larkin. Among our primary tasks will be:

- Work with the coronagraph team to optimize the configuration of the coronagraphic stops.
- Study how to optimize the instrument sensitivity including optimizing the detector performance, spectral format and modeling the atmosphere and background sources.
- Contact vendors to determine the best image slicing technology.
- Define the basic size and characteristics of the optical elements.
- Measure scattered light properties within an existing spectrograph at UCLA.
- Perform a preliminary costing analysis of the instrument.