Gemini ExAOC design study (NSF Center for Adaptive Optics)

Progress Report 1: August 2004

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Accompishments / status summary:

Overall the design study is on track. Our multi-institution team is functioning smoothly. The detailed science case evaluation has led to a set of science-driven instrument requirements that are now being implemented as subsystem requirements documents are written. We are currently in an instrument-definition phase, and have had excellent progress in each subarea, especially the development of science instrument strawmen, optimal AO control, and a coronagraph/calibration architecture.

Primary milestones:

1.1.1	Commence work	6/7/04	**Complete**
1.2.1	kick-off workshop @ UCSC	6/7/04	**Complete**
1.2.2	science workshop @UCB	7/19/04	**Complete**
1.2.3	mid-term review @ HIA	10/11/04	
1.1.2	Final science instrument definition	10/11/04	
1.1.3	Deliver draft of Initial OCDD	10/25/04	
1.1.4	Deliver draft of Initial FPRD	10/25/04	
1.1.6	Deliver preliminary WBS, schedule, and budget	9/17/04	
1.1.5	Submit Design Study Documentation Outline	11/15/04	
1.1.7	Deliver revised Initial OCDD	1/3/05	
1.1.8	Deliver revised Initial FPRD	1/3/05	
1.2.4	pre-CoDR @ UCSC	1/10/05	
1.1.9	Deliver Design Study Documentation	1/28/05	
1.1.10	Conceptual Design Study Review (CoDR)	TBD	
1.1.11	Completion of all work	TBD	

Table 1: List of primary milestones.

1.0 Project Management

1.1 Interim milestones

Interim milestones have been established for each institution (see Table 2). At present, all Interim Milestones that are due have been completed (some at a draft level), with documents submitted and reviewed within the project. Future milestones are on track. Details of each institution's progress to date are included in the remainder of this document.

Effort (team)	MS 1	MS 2	MS 3	MS 4	WBS MS
system requirements, error budget (Macintosh)	initial error budget & preliminary subsystem goals – 7/16/04 **Complete**	final error budget & subsystem goals – 9/20/04	system performance verified with simulations – 12/13/04	final system performance section of CoD – 1/10/05	prelim. budget inputs – 9/10/04
science case (UCB, et. al.)	completed science-drivers matrix and support – 7/23/04 **Complete**	Draft Initial OCDD – 10/11/04	Initial OCDD – 12/13/04	final science case section of CoD – 1/10/05	prelim. budget inputs – 9/10/04
system engineering (HIA)	formal subsystem interfaces – 8/26/04 **In progress**	Draft Initial FPRD – 10/11/04	Initial FPRD – 12/13/04	final documentation package – 1/28/05	prelim. budget inputs – 9/10/04
adaptive optics (LLNL)	preliminary optical requirements and specifications - 7/30/04 **Draft complete**	final subsystem requirements, optical conceptual design (including WFS), and strawman AO computer design – 10/11/04	finalized algorithms and AO computer conceptual design, final DM selections, and final CCD selection – 12/28/04	final AO conceptual design – 1/10/05	prelim. budget inputs – 9/10/04
coronagraph (AMNH)	Preliminary optical requirements and specifications - 7/30/04 **Draft complete**	science instrument interface definitions – 8/30/04	fully fleshed-out coronagraph designs – 10/11004 completed simulations and manufacturability analysis – 12/15/04	final coronagraph conceptual design – 1/10/05	prelim. budget inputs – 9/10/04
calibration (JPL)	strawman calibration approach (hybrid & dithering) and specifications – 7/30/04 **Complete**	final calibration specifications and interface definition – 10/11/04	simulations demonstrating contrast performance with coronagraph and science instrument – 12/15/04	final calibration conceptual design – 1/10/05	prelim. budget inputs – 9/10/04
IFU (UCLA)	Preliminary optical requirements and specifications – 7/30/04 **Complete**	preliminary performance modeling, coronagraph interface definition – 8/30/04	fully fleshed-out instrument design – 10/11004	completed performance modeling – 12/15/04 final science instrument	prelim. budget inputs – 9/10/04

Effort (team)	MS 1	MS 2	MS 3	MS 4	WBS MS
MWI (UdeM)	preliminary optical requirements and specifications – 7/30/04 **Complete**	preliminary performance modeling, coronagraph interface definition – 8/30/04	fully fleshed-out instrument design – 10/11004	conceptual design – 1/10/05	prelim. budget inputs – 9/10/04
opto-mechanical (UCO/Lick)	flexure analysis of Keck WFS design – 7/30/04 **Complete**	preliminary opto-mechanical design (for AO and coronagraph) and specifications – 10/11/04	preliminary opto-mechanical design (for WFS) and specifications – 11/25/04	final opto-mechanical conceptual design – 1/10/05	prelim. budget inputs – 9/10/04
upper/mid-level SW (UCO/Lick, HIA)	preliminary system data flows, HW/SW subsystem interfaces, and telescope interface – 8/26/04 **In progress**	Supervisory / Component Controller Computer (SCC) conceptual design – 9/17/04	Engineering User Interface conceptual design – 10/5/04	final upper/mid-level SW conceptual design – 1/10/05	prelim. budget inputs – 9/10/04
management (LLNL)	track project, monthly reports, etc.			final WBS, schedule, budget – 1/28/05	prelim. budget – 9/17/04

Table 2: Intermediate milestones

1.2 Communication

To date, project communication has been plentiful and productive. In summary:

a. a project kickoff meeting/workshop was held on June 7th and 8th
b. a science workshop was held on July 19th
c. two coronagraph telecons have been held on July 9th and July 30th
d. a project-wide video/telecon (2 hrs) was held on August 3rd
e. project-lead telecons have been held on most weeks
f. many ‘informal’ discussions have taken place at SPIE, at other meetings, on the phone, and by e-mail
g. a full-up web site is nearly up (this has been delayed by computer problems at Santa Cruz; a ‘temporary’ web site and e-mail have been used in the meantime)

Communication within the project has been as good or better than hoped, with people participating willingly and taking the initiative when necessary.

1.3 Finances

As per our proposal, formal financial reporting will take place quarterly with the first report to be submitted next month. Informally, at present, all institutions are running at or below budget. The contract between UCSC and Gemini has been signed; the subcontracts to HIA and UCLA have not yet been signed, primarily due to UCSC federal-standards requirements for documenting matching funds. Work at HIA/Montreal and UCLA has been taking place using matching funds and has not been delayed.

2.0 Science case development

The science team milestone during this period is to review and finalize the instrument requirements matrix. This matrix connects ExAOC science goals with properties of the instrument. For the purposes of defining these requirements the science goals are: 1) discovery and quantification of the planetary population in field stars and in nearby young clusters and associations; 2) exploration of debris disk systems; 3) solar system science, including binary asteroids, Titan's atmosphere and Ionian volcanism.

On July 19, eight members of the science team met in Berkeley (Chiang (UCB), Doyon (UdM), Graham (UCB), Johnstone (DAO), Kalas (UCB), Macintosh (LLNL), Marchis (UCB) & Patience (UCLA)) with telephone participation by Yanquin Wu (Toronto) and Adam Burrows (U of Arizona). Although not a member of the original science team, we have since invited Prof. Burrows to join us to advise us on the theory of cooling planets and their atmospheres.

The most significant progress achieved at this meeting was related to optimization of AO system parameters (sub-aperture size and loop bandwidth), inner working distance, operating wavelength, exploration of speckle noise suppression and assembly of target lists for young cluster and association surveys. Figure 1 shows an example of the AO phase space exploration for four loop (rows: 0.5, 1.0, 1.5 & 2 kHz)) and three sub-aperture sizes (columns: 12, 18 & 25 cm). (Compare with Fig. 3 from the proposal).

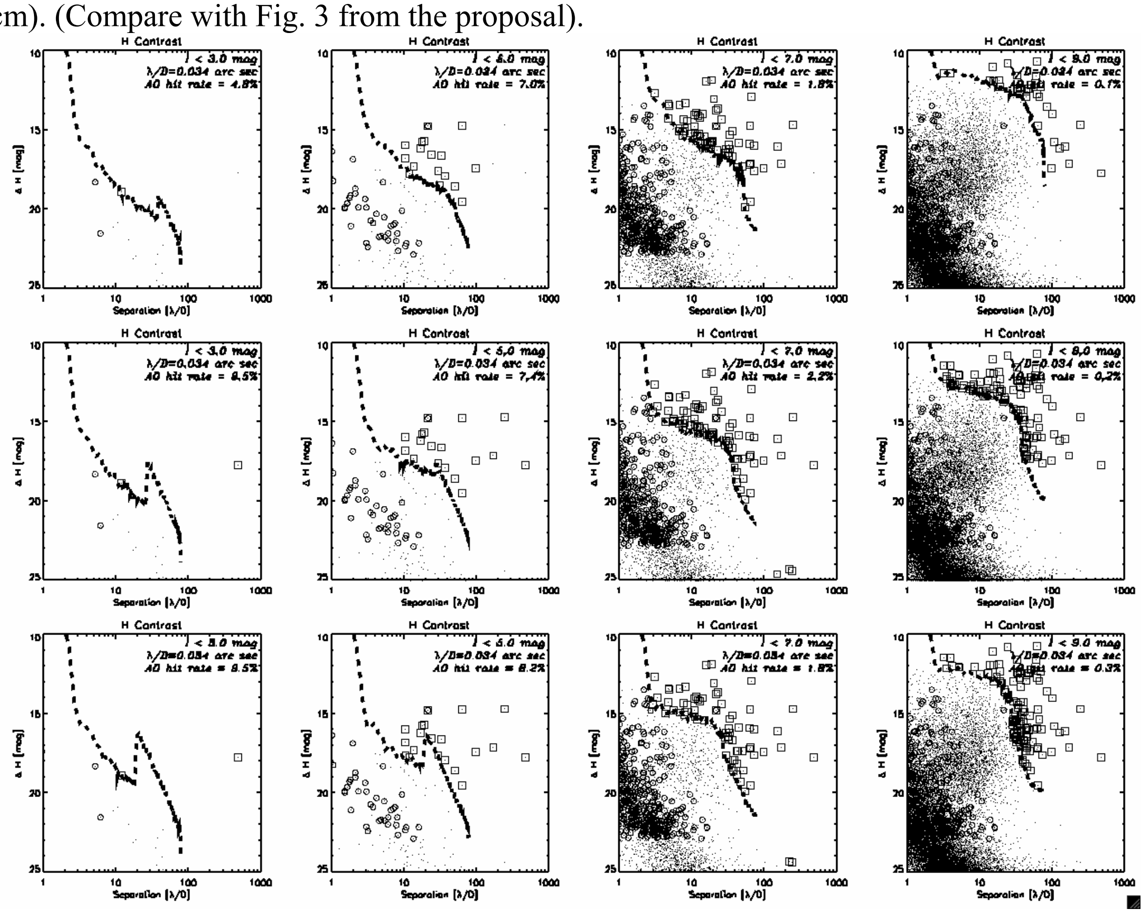

Figure 1: Exploration of the AO phase space for four target star magnitudes (columns: mI=3, 5, 7, and 9) and three sub-aperture sizes (rows: 12, 18 & 25 cm). Each plot shows detectable companion contrast versus angular separation assuming broadband imaging with no speckle suppression. The AO system model uses a simple rather than optimal controller. 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 sigma) for a 1 hour exposure at 1.65 microns. These simulations show that to get a high detection rate on a significant target sample will require speckle suppression; calculations show reducing speckle noise by 1/16 via multiwavelength imaging will produce an acceptable detection rate.

This tool will allow us to evaluate optimal subaperture size and loop parameters for extrasolar planet surveys As part of this exercise we have completely rewritten our ExAOC SNR calculator. The previous version treated only speckle, background and detector noise. The new version also includes all sources of photon shot noise, including that from the PSF halo, as well as gain noise due to flat fielding errors. The new SNR calculator confirms our previous approximations, but permits a quantitative exploration of the effects of speckle suppression and allows us to specify the corresponding flat field accuracy.

The conclusions of the science team regarding requirements were presented at the project-wide telecon on August 3. The description of these requirements is being refined in the light of this discussion and a final version is being prepared for release by August 16. See Appendix 1 for the preliminary science requirements.

3.0 System design and performance modeling

A preliminary system contrast/error budget spreadsheet has been developed (Table 3); the underlying methodology is discussed in detail in an internal document. Stochastic / Monte Carlo simulations have been used to predict system performance in more detail over a grid of potential subaperture sizes, update rates, and target star magnitudes which were used in the evaluation of the planet discovery reach discussed in the science case section. These simulations show that to achieve the science goals on a broad magnitude range of target stars will likely require some degree of post-processing suppression of speckle noise, e.g. through multi-wavelength imaging.

Scattered light source	low freq. WFE (nm)	mid freq. WFE (nm)	high freq. WFE (nm)	all freq WFE (nm)	Speckle lifetime (seconds)	PSF intensity 0.4 arcsec	PSF noise 0.4 arcsec 1 hour
Atmosphere		2.00	30.75		0.16	6.0E-08	7.7E-11
Telescope primary/secondary		0.50	20.00		1772.04	3.8E-09	5.0E-10
Telescope vibration	0.00	0.10	0.00	0.00	**1.00**	1.5E-10	4.8E-13
Initial calibration	5.00	1.00		5.00	1772.04	1.5E-08	2.0E-09
Atmospheric bandwidth	16.36	17.41	12.13	16.36	0.16	3.2E-06	4.0E-09
WFS measurement		40.17			0.01	2.4E-05	6.3E-09
Uncorrectable internal errors		0.00	23.00		1772.04	1.0E-20	1.3E-21
Quad cell changes	0.33	0.19	0.00	0.33	1772.04	5.7E-10	7.6E-11
System Flexure	*10.00*	*1.00*	*0.00*	*10.00*	*1772.04*	*1.5E-08*	*2.0E-09*
Residual diffraction						*5.00E-08*	
Post-coronagraph aberrations	8.21	4.86	3.00	8.21	1772.04	2.2E-08	2.9E-09
Scintillation					0.16	1.0E-06	1.3E-09
Atmospheric chromatic errors						*TBD*	*TBD*
Internal chromatic errors						*TBD*	*TBD*
Internal static intensity errs						2.4E-08	3.1E-09
Photon noise							3.7E-09
Total	**19.81**	**43.85**	**44.96**	**65.86**		**2.9E-05**	**1.8E-08**

Table 3: Preliminary error budget for the ExAO system in direct broadband imaging mode. Assumptions and methodology are discussed in a separate document. (Subaperture size d=13 cm, r0=20 cm at 500 nm, target star m_I=5 I-H=0.6. Terms in *italics* are preliminary. PSF noise is calculated ofr a 1-hour

exposure. PSF intensity and PSF noise are normalized with respect to the peak intensity of the coronagraphic PSF, so that a PSF noise of 1.5×10^{-8} would represent a 5-sigma detection of a companion with a contrast relative to its primary of 7.5×10^{-7}.

4.0 Systems engineering

Subsystem performance requirements are being defined based on the science requirements and error budgets discussed above. These will be circulated and reviewed within the project over the next weeks. Interface documents will be generated.

5.0 Adaptive optics

5.1: AO optical design

Preliminary optical requirements for the AO subsystem have been generated based on the error budget; these appear practical to achieve within the Gemini instrument envelope.

5.2: AO control

AO system control has been extensively studied. Poyneer and Veran have devised a suitable basis set for our Fourier-domain wavefront reconstructor and shown that it provides a natural match to the ExAO high-contrast PSF, in that individual Fourier modes correspond to locations in the PSF. We have a preliminary implementation of a automatic gain optimization process, similar to ALTAIRs, on this much larger modal basis set. This optimal gain process may significantly improve dim-star performance relative to the error budget and performance models in sections 2 and 3, and produce a system as self-optimizing as ALTAIR. The computational requirements appear small compared to the main wavefront reconstructor.

5.3: AO components

Our team provided input to Gemini and ESO for a RFP for 256x256 ExAO-suitable CCD detectors.

We have continued testing of 1024-actuator MEMS deformable mirrors in the Laboratory for Adaptive Optics testbed. Preliminary results show that we can flatten a MEMS mirror to <2 nm RMS in the controlled spatial frequency range and 6 nm RMS overall.

However, Boston Micromachines has identified a new MEMS failure mode. Exposure to humidity >50% while the MEMS is operated at high voltage causes an andodic oxidation phenomenon which results in actuators losing performance. After this phenomenon caused partial failure of our first two MEMS devices we have obtained a MEMS with a hermetically sealed window. We will evaluate the effects of this on the real instrument.

6.0 Coronagraph

The coronagraph team worked on the baseline coronagraph design and current hardware status, plate scales, and interface details with the AO and Calibration systems and Science Camera. Numerical studies of suppression on obscured apertures using Apodized Pupil Lyot Coronagraphs were developed and performed (analytical results only hold for unobscured apertures). Discussions with the Lead and Calibration teams were held, and e-mail contact between the Coronagraph Team and the Lead, Science Camera and Calibration, Teams enabled early decisions to be made.

The coronagraph team made contact with the Princeton TPF Coronagraphy group and studied the current state of Shaped Pupil solutions of the high dynamic range imaging problem. The baseline EXAOC design was formulated to enable use of a SP coronagraph (with an image plane stop to reduce stray light inside the science camera) as well as the coronagraphic train of a possibly apodized entrance pupil, occulting stop, and Lyot pupil. A pupil design taking spiders and a central obscuration into account, with a contrast of 10^{-7} at 4-5λ/D, was obtained from

Princeton (Figure 1). Current in-lab suppression of $3x10^{-8}$ has been demonstrated at $5\lambda/D$ with similar masks at both Princeton and UCSC. These masks do have the disadvantage of a restricted search area, requiring two images at different rotations to fully search a target star; we will explore the effects of this with the science team. We are also studying band-limited Lyot coronagraphs and greyscale apodization; the base coronagraph architecture is design to be flexible enough to support all these approaches.

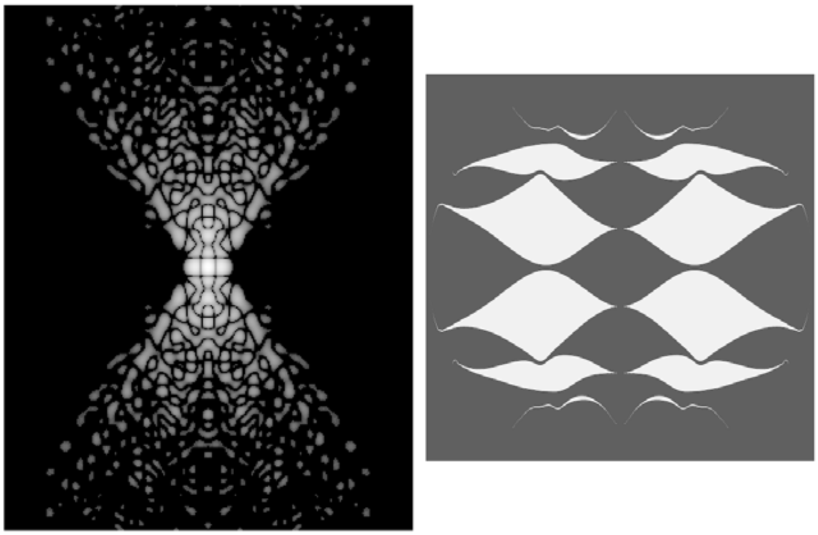

Figure 2. PSF (left) on a log stretch, and pupil mask (right) with a 20% secondary obstruction and secondary support spiders, optimized with 4 openings per quadrant of primary, and a requirement of 10^{-7} contrast from 4-5λ/D in a wide wedge.

7.0 Calibration

The goal of the calibration is to measure the time-averaged wave front error in the science arm of the instrument. In our baseline case, this measurement is done via interference with a reference wave front. The reference is generated from the light that would otherwise be rejected from the occulting mask. (Here, no reference is made to a particular coronagraph design (shapted pupil, classic Lyot, nulling coronagraph). This light is spatially filtered and then interfered with some light (~20%, spectrally neutral) in the science arm. Phase-shifting interferometry allows us to estimate both the amplitude and phase of the wave front in the science arm.

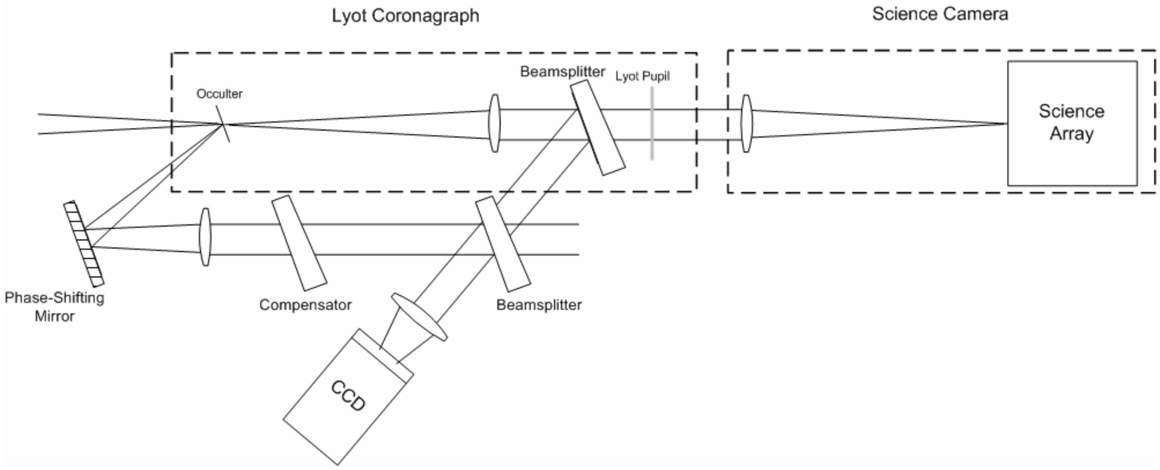

Figure 3: Strawman calibration architecture based on a phase-shifting interferometer in series with a Lyot coronagraph.

The team has advanced the proposed calibration method on a few different fronts. Work continues on improving the fidelity of the simulations for the interferometric wave front sensor. The model currently includes atmospheric realizations (phase only), closed loop adaptive optics correction, band-limited coronagraph and interferometer wave front sensor. Our simulations will soon include the effect of photon noise, read noise, a wide optical bandpass and control system delay. In the near future, we will attempt to integrate our calibration procedure with the strawman coronagraph system that has been recently proposed. Our team has created the optimum pixilated version of the baseline shaped pupil for use by both us and the coronagraph team.

8.0 Integral field unit

The IFU team has been developing strawman designs for the integral field spectrograph concept. In particular, we've produced a set of analytic expressions and a spreadsheet that allows us to set the focal ratios, lenslet pitch, focal length and other parameters as a function of spectral resolution, field of view and detector properties. A particularly difficult aspect of this modeling has been the inclusion of pupil aberrations that occur when you subsample a diffraction limited image. Few other groups have addressed the aberration of pupils with diffraction limited slits or apertures and we have found no discussion in the literature on the effects of very fine subsampling. Since speckle suppression is critical for planet detection and is likely to require better than Nyquist sampling of the focal plane, and since any lenslet based instrument is a pupil spectrograph or imager, pupil blur is extremely important (Figure 4).

This much larger pupil must be demagnified onto the detector in order to interleave the spectra (IFU), or fit neighboring images (multiwavelength imager). The bottom line, is that reasonable IFU's can be designed to handle this effect, but it makes the spectrograph optics faster than predicted from geometric optics. An 8 page design document and a spreadsheet have been produced to describe this effect and other IFU issues in detail.

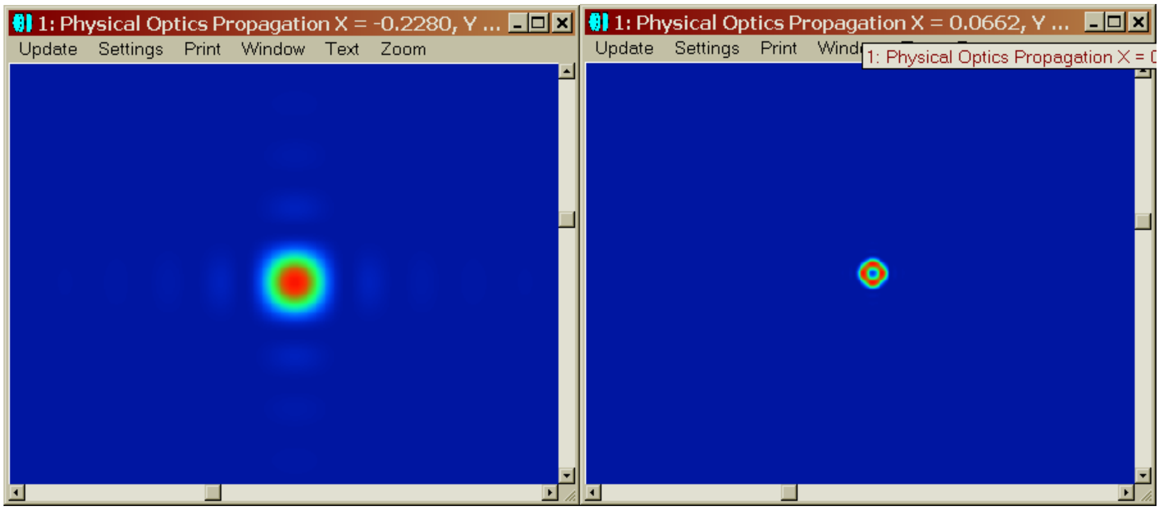

Figure 4: The panel of the left is a pupil image formed by a large aperture (3λ/D) and shows the primary mirror with central obscuration. The FHWM is 19 microns with a 90% encircled energy diameter of 27 microns; essentially the same as the prediction from geometric optics for this configuration. On the right, the lenslet Nyquist samples the focal plane (λ/2D) but the geometric pupil should have the same size. Diffraction, however, blurs the pupil so that it now has a FWHM of 48 microns and a 90% diameter of 174 microns.

9.0 Multiwavelength imager

The original multi-color detector assembly concept sketched in the proposal, one involving micro-filters coupled to a micro-lens array, has been replaced by a similar but more flexible concept consisting of a micro-lens array feeding a 4-way beam splitter yielding four narrow-band (R~50) images (1.52, 1.58, 1.64 and 1.70 µm) each one spanning one quadrant of a Hawaii-2RG detector. This design is not only immune against non-common path aberrations which plague the performance of current generation of multi-wavelength imagers (MWI) like TRIDENT, the flux contamination across wavelengths is completely eliminated. Minimizing this wavelength crosstalk is crucial for maximizing speckle noise attenuation. This MWI concept is in effect an IFU with four discrete wavelength samples free of wavelength crosstalk. A document describing a strawman MWI design with a FOV of 5.3”x5.3” has been produced. Optical design work is currently underway at INO.

The UdeM team has also conducted laboratory tests as a proof of concept of the MWI. Figure 5 shows a laboratory PSF dissected by a micro-lens array mounted very close to a Hawaii-1 detector working in monochromatic light (1.57 µm, 1%). The PSF on the right shows the reconstructed PSF. These data have allowed the team to test various PSF interpolation algorithms and test the accuracy by which PSFs can be subtracted from one another. The current data yield a PSF attenuation of 10^{-2} beyond a radius of 1 λ/D which is very encouraging. These lab results and the MWI concept presented here have been presented at the Glasgow SPIE conference (Lafrenière *etal*).

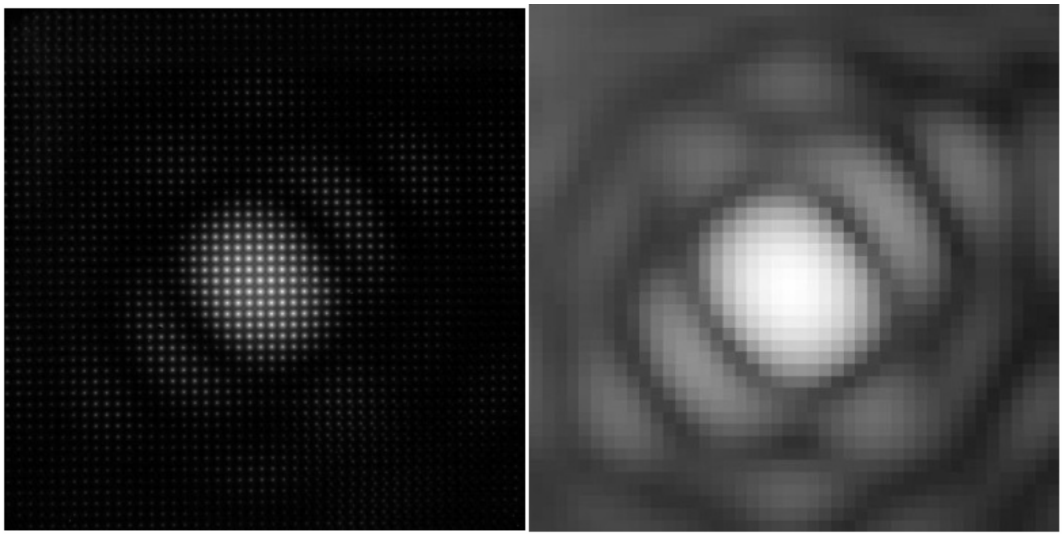

Figure 5: Laboratory PSF dissected by a microlens array (left) and reconstructed PSF (right).

10.0 Optomechanical design

We have established a set of baseline optical requirements and begun exploring approaches to achieving these requirements. Mechanical analysis has been carried out using a previous ExAO design for the Keck observatory (Macintosh et al 2004 Proc. SPIE in press); as one would expect, flexure effects in this Naysmith-based design are significant, but it provides a useful starting point for Gemini analysis. Detailed optical design will be carried out once the coronagraph requirements and architecture have been completed.

We have also begun wave optics modeling of a simple strawman AO system to evaluate the effects of static intensity errors caused by phase errors on intermediate surfaces. This effect may set strict requirements for the overall optical tolerances.

11.0 Software

The software group has met by telecon several times. System data flow and software requirements are being drafted, together with ICDs for the interface between OCS and ExAO, DHS and ExAO, and internal interfaces between the ExAO supervisory control computer (SCC) and the AO computer, science instrument computer, and components controller.

12.0 Risk issues and conclusion

Overall the design study is on track. Our multi-institution team is functioning smoothly. The detailed science case evaluation has led to a set of science-driven instrument requirements that are now being implemented as subsystem requirements documents are written. We are currently in an instrument-definition phase, and have had excellent progress in each subarea, especially the development of science instrument strawmen, optimal AO control, and a coronagraph/calibration architecture.

One technical risk identified to date is the MEMS humidity issue discussed in section 5.3. We believe this can be controlled by sealing the MEMS or the instrument as a whole, but the feasibility of this approach needs to be evaluated and perhaps conventional phase correctors should be studied in more detail.

Appendix 1 (following pages): Science requirements

	Exoplanet field survey	**Cluster survey**	**Exoplanet properties**	**Debris & protostellar disks**	**Solar system**
Contrast vs. angular separation	Required: 5% planet recovery at *H*. C = 3e-7 at 4λ/D, 6e-9 at 30 λ/D (1 hr 5- σ). Includes speckle suppression.	Goal: 20% planet recovery. C < 3e-7 between 3–15 λ/D at H (1 hr 5-σ)		Detect HR 4796A/100 pole on	
WFS mag. limit & λ	Required: 700 - 900 nm, *I* = 7 mag. Bright limit *I* = -2 mag.	Required: Lock AO on G stars in Hyades (*I* < 8 mag).		Goal: lock AO on T Tauri stars (*I* = 10 mag.). Bright limit *I* = -2 mag. (selectable).	Lock AO on extended objects, e.g., Io diameter ~ 1.2 arc sec (selectable)
Speckle suppression	Required: multi-color speckle noise suppression > 16	Required: multi-color speckle noise suppression > 32		Required: polarimetry mode: speckle noise suppression > 16	
Wavelength range	Required: 1.1-2.4 μm. Goal: sensitivity to young planets 0.9 < λ/μm < 4.2. Wavelength in selectable *IJHKLp* bands.	Required: 1.1-2.4 μm.		Required: polarimeter works at 2.2 μm. Goal: constrain grain size distribution 0.9 < λ/μm < 4.2.	Goal: 0.8 μm operation for max. resolution at moderate Strehl (selectable)
Spectral resolution	Required: multi-color speckle rejection, *R* ~ 30 or 5 or more "colors" per band. Goal: simultaneous *J&H or H&K*.		Requirement: $T_{eff}/\log(g)$ diagnostics *R* ~ 20-50 in *JHK*.	Goal: *R* ~ 100 for ice and Si bands (higher resolution may be selectable)	Ice mineralogy
Polarimetry	Distinguish exoplanets & zodiacal blobs. Required: sensitive to 1% linear polarization.			Dual channel polarimetry for sensitivity to dust scattering.	Atmospheric hazes
Throughput			Goal: *H* band η > 25%, top of atmosphere to photo-electrons.		
Detector	Required: detector noise increases residual speckle & photon shot noise by < 20% at *R* ~ 30		Goal: detector noise increases residual speckle & photon shot noise by < 20% at *R* ~ 100		
Emissivity	Minimize AO & coronagraph mask emissivity (cold?). Goal: equivalent emissivity < 15% at 273 K				

	Exoplanet field survey	Cluster survey	Exoplanet properties	Debris & protostellar disks	Solar system
Operability, reliability	Requirement: Nominal operation in best 50% seeing. Survey 2000 stars in 200 nights or 90% open shutter			Accumulate deep exposures	Capture rare events
Zenith distance limit	Required > 30°, goal > 45 degrees				
Accessible Dec. range (-60 < dec < 0)	Requirement: TBD–young field stars	Goal: young assoc. vs. nearby clusters, esp. Hyades □= 15°			Goal: -25° < □< 25°
Astrometric accuracy	Required: location of target star on FPA is set or measured to < 1 mas, 1□ (one axis).	Position of companions to 1 mas, 1□, (one axis).	Orbital eccentricity		
Flat fielding accuracy	Better than 1% on all spatial frequencies			Sensitivity to surface brightness	
Photometric accuracy	Required: absolute 10%, relative 2%		Magnitudes & colors and depths of H2O bands		
Pixel sampling	Required: 1.5–2 Nyquist at H (10-13 mas) for speckle suppression. Selectable scale for longer □				
Field of view	Required: FOV 3.”6 x 3.”6 at H. 180° sector instantaneous. 360° viewable by mask rotation			Outer extent of debris disks. FOV in polarimetry mode can be 1.”8 x 3.”6	