New Generation Adaptive Optics (NGAO): System Design Review

April 21st & 22nd 2008

Review Panel Report to Director, Keck Observatory

Prepared by the review panel:

Norbert Hubin (Chair)
Bob Fugate (Co-chair)
Brent Ellerbroek
Andrea Ghez
Gary H. Sanders
Nick Scoville

Acknowledged:

Released:

1. INTRODUCTION

1.1 SCOPE

This document is the report of the review panel established by the Director of Keck Observatory to assess the current state of the project to construct a Next Generation Adaptive Optics (NGAO) system for the W. M. Keck Observatory. The report is based on documentation provided to the panel and briefings and discussions during a day and a half System Design Review held 21 and 22 April 2008 at the Burlingame, CA Marriot Hotel near the San Francisco Airport.

The Keck NGAO facility team consists of:

P. Wizinowitch (Project Manager), C. Max (Project Scientist), R. Dekany (COO Project Manager), D. Gavel (UCO Project Manager), E. Johansson (system engineering & Non Real Time Control), C. Neyman (system engineering, laser facility), V. Velur (wavefront sensors), M. Reinig (Real Time Control), R. Kupke & C. Lockwood (AO Optomechanics), D. Le Mignan (Science Operations & Handover), S. Adkins (Laser), J. Chin (laser facility)

The review panel members are:

- Norbert Hubin (ESO), nhubin@eso.org , (Chair)
- Robert Q. Fugate (NMT), rqfugate@comcast.net **(Co-chair)**
- Brent Ellerbroek (TMT), brente@caltech.edu
- Andrea Ghez (UCLA), ghez@astro.ucla.edu
- Gary H. Sanders (TMT), sanders@tmt.org
- Nick Scoville (Caltech), nzs@astro.caltech.edu

1.2 Applicable and Reference Documents

The NGAO System Design Review Documentation provided to the review panel is available at:
http://www.oir.caltech.edu/twiki_oir/bin/view/Keck/NGAO/SystemDesignReview

The documents were made available to the review panel March 29th (apart from the Management Plan). The Management Plan was provided April 4th.
The review Panel provided a list of questions to the NGAO team before the review meeting. These questions were answered by the NGAO team April 19th. Questions and answers are attached as Appendix A.

2. Charge to the Review panel

The charge to the review panel is as follows:

1. Assess the impact of the science cases in terms of the competitive scientific landscape in which the system will be deployed.
    - Are the science cases given in the Science Case Requirements document complete and compelling?
2. Assess the maturity of the science cases and science requirements and the completeness and consistency of the technical requirements.
    - Are the science requirements clear, complete and well documented?
    - Is a clear flow down established from the science requirements to the technical requirements?
    - Are the performance and error budgets complete and consistent with the science requirements?
    - Are the technical requirements clear, complete and well documented?
3. Evaluate the conceptual design for technical feasibility and risk, and assess how well it meets the scientific and technical requirements.
    - Does the performance predicted for the conceptual design meet the scientific and technical requirements given in the System Requirements document?
    - If the predicted performance of the conceptual design does not meet the scientific or technical requirements are there adequate plans for addressing these deficiencies as the project continues?
    - Does the conceptual design appear feasible?
    - Is the risk identification complete, and if not, what additional risks should be considered?
    - Are the risk mitigation efforts and future plans for risk mitigation likely to result in retirement of all critical risks?
4. Assess whether the design can be implemented within the proposed schedule and budget.
    - Are the plans for completion of the project, including the cost estimate, schedule and budget to completion, sufficiently detailed?
    - Is the methodology used to develop the cost estimates sound?
    - Is the proposed schedule to completion realistic?
    - Is the proposed budget to completion realistic?
    - Is there sufficient management reserve (contingency) allocated in the proposed budget to completion?
5. Evaluate the suitability and effectiveness of the project management, organization, decision making and risk mitigation approaches, with an emphasis on the next project phase (preliminary design) and also with respect to the entire project.
    - Does the performance of the project to date support the project’s approach to management and decision making?
    - Is the project’s proposed future approach to management and decision making likely to succeed? What modifications would be advantageous to assure the success of the entire project?
6. Provide feedback on whether the overall strategy will optimize the delivery of new science.
    - Are there possibilities for staged implementation or descopes that are viable in terms of the science requirements?

7. Gauge the readiness of the project to proceed to the preliminary design phase.
    - Has the project adequately defined the objectives, work breakdown structure and task plan for the next design phase?
    - Is the technical design sound?
    - Is the design concept and architecture adequately documented?
    - Are the resources identified for the next design phase sufficient to address the scope of work?

Issues related to the availability of funding for the project are outside the scope of the review. The panel should assume for the purposes of this review that the necessary funding can be obtained in a timely fashion.

The scope of this review is the AO and laser guide star portion of the NGAO system. The instrumentation for the NGAO system has not been developed beyond initial descriptions of the needed capabilities. Comments on these capabilities are welcome in the context of how they impact the ability of the complete NGAO system to execute the science cases.

3. NGAO System Design Review Agenda

April 21st 2008

9:00 Welcome & Introductions (Armandroff)
9:10 Charge (Lewis)
9:20 Review Panel closed session (Hubin)
9:45 Re-entry for non-Panel participants
9:50 Comments from Chair (Hubin)
10:00 Presentation Approach (Wizinowich)
10:05 Science Cases & Science Requirements (Max) SCRD
11:15 Break
11:30 Requirements (Gavel) SRD, FRD
12:00 Design (Gavel) SDM
12:30 Lunch
13:30 Design (Gavel) SDM
14:00 Performance Budgets (Dekany) SDM
14:45 Project Management (Wizinowich) SEMP
15:15 Risks (Wizinowich) Risk KAONs
15:45 Break
16:00 Cost Estimate (Dekany) SEMP
16:40 Schedule & Budget (Wizinowich) SEMP
17:20 Conclusion (Wizinowich)
17:30 General Discussion & Questions (Hubin et al.)
18:00 Closed Session

April 22nd 2008

8:30 Review Panel closed session (Hubin)
9:30 Questions for NGAO EC as needed
10:00 Review Panel closed session
11:30 Review Panel draft report to Directors & NGAO EC (Hubin)
12:15 Lunch
13:00 End

4. Executive Summary

The review panel offers its sincere congratulations to the NGAO design team for its excellent work to date in the Systems Design phase of the NGAO project, for the high quality of the answers to questions posed by the panel and for the highly-focused presentations during the review.

The review panel believes that Keck Observatory has assembled an NGAO team with the necessary past experience (Science exploitation of the existing AO systems, development & operation of laser guide star adaptive optics at Keck, Palomar and Lick Observatories, development & operation of the high angular resolution imaging and 3D spectroscopy instrumentation, and the operation and calibration of AO-based instrumentation) needed to develop the Next Generation Adaptive Optics facility for Keck. It is a sound, though aggressive, strategy to be among the first observatories to develop and depend on advanced laser guide star AO systems as a means to maintain Keck's leadership in ground-based observational astronomy for the immediate future.

The panel also believes that NGAO is an important pathfinder for the 2nd generation of AO based instruments for future Extremely Large Telescopes as emphasized in the "Roadmap for the Development of United States Astronomical Adaptive Optics" report issued April 18th 2008.

The NGAO Science cases are mature, well-developed and provide enough confidence that the science expected to be produced with the Keck NGAO system will be unique within the current landscape. The NGAO science cases (high-redshift galaxies, black hole masses in nearby AGNs, general relativity at the galactic center, planets around low-mass stars, and asteroid companions) complement nicely the expected science provided by JWST, ALMA, Gemini GPI, ESO SPHERE and is scientifically a precursor of the TMT 1st light Multi-Conjugate AO system NFIRAOS. NGAO is also an important pathfinder for the next generation of high Strehl open loop Adaptive Optics systems to be implemented on the ELTs.

The science requirements are comprehensive, and sufficiently analyzed to properly flow-down technical requirements. However, the review panel believes that the actual cost/complexity to science benefits of the required IFS multiplex factor of 6 should be reassessed. The IFU spaxel size and Ensquared Energy requirements should be confirmed using a representative set of High-z galaxies: the review panel recommends considering the potential scientific advantage of having several spaxel sizes. The predicted Sky Coverage for NGAO is essential and should remain a top requirement for the project. The PSF knowledge accuracy needs to be carefully specified from both the astronomical and technical view point. The review panel welcomes the potential upgrade path to Multi-Conjugate Adaptive Optics (MCAO) to address the remaining stellar populations in crowded fields science case.

The error budget is sufficiently developed at this stage of the project and meets the science requirements. The specified performance of NGAO is most challenging and the detailed design will require even more attention to maintain an accurate and reliable error budget during the next phases of the project. In particular, the panel believes special attention is needed in the areas of real-world laser power requirements and minimizing implementation errors associated with the Multi Object AO system's open-loop control of MEMs deformable mirrors. The panel recommends increasing emphasis on simulations and validations with independently developed codes.

The system technical requirements are clear, complete and well- documented. The requirements and analysis at the subsystem level (laser devices and facility, LGS WFS, LOWFS, RTC, Control system …) need additional work.

The performance predicted for the conceptual design meets the scientific and technical requirements. However, the sodium photon return, the LGS wavefront sensor performance and possibly the low order wavefront sensor performance assumed seems optimistic and will require careful analysis during preliminary design. The expected performance of MOAO should be confirmed to the accuracy level required by NGAO, for instance, using the Villages on-sky experiments.

The review panel is concerned by the lack of a well developed fall-back plan in case NGAO is unable to meet the scientific and technical requirements. The panel recommends that the NGAO team develop a more detailed risk mitigation plan – beyond that shown in the technical and programmatic risk matrices including decision trees and sublevels. Apart from the high technical risk due to the complexity of NGAO, it is essential that the NGAO team develop a fall back plan and/or a staged implementation plan in case of funding shortage. In particular, the risk associated with the availability of the laser, sodium photon return flux, practical implementation of MOAO, point spread function accuracy and estimate, detector readout noise, and interface/requirements of the focal plane instrumentation need further analysis and a detailed, phased mitigation plan.

The review panel has not identified any fundamental show stoppers in the conceptual design documented and presented. However, the proposed NGAO concept is complex, technically and managerially very risky and will require considerable effort and time to implement. The review panel recommends that the NGAO team reassess the concept choices with a goal to reduce the complexity and risk of NGAO while keeping the key science objectives. In particular, the potential decrease of complexity brought by the reduction of IFU numbers (if scientifically acceptable) and the possibility to have only one (or two with NGS) AO optical paths for all focal plane instruments might be considered.

The review panel acknowledges the effort made by the NGAO team to estimate the cost, labor and schedule of the NGAO project. This is definitely a difficult task at the conceptual design stage for a project as complex as NGAO. However, based on the cost and schedule of past and planned projects of lower or similar complexity, the review panel believes that the NGAO project cost and schedule are not reliable and may not be realistic. Contingencies are also too tight. In particular, the time of 18 months allocated for the manufacturing and assembly and 6 months for integration and test, is probably optimistic by a large amount.

The review panel believes that an estimate of the instrumentation and associated run-out cost and schedule in addition to the NGAO project cost and schedule must be included to assess funding shortage risks, schedule and human resources conflicts and scientific priorities.

The project's approach to management and decision making for the system design phase was appropriate and cost effective. The System Design deliverables are complete. For the preliminary design phase, the NGAO proposed management structure seems appropriate. The role and authority of the Project Manager, Project Scientist, System Engineer and Configuration Control Board should be clearly described and agreed upon in the management plan. The review panel recommends appointing a full-time System Engineer for the Preliminary Design phase. However, for the Detailed Design phase and beyond we suggest that the WBS, organization and management approach be fully oriented to deliverables and to responsible managers for each deliverable as opposed to the current focus on institutional setting and project phase.

The NGAO design drivers are: high Strehl ratio (or high Ensquared Energy), high sky coverage, moderate multiplex gain, PSF stability accuracy and PSF knowledge accuracy. The PSF uniformity accuracy is also desirable (upgrade path to Multi Conjugate AO). These design drivers are well justified by the key science cases which themselves fit well into the scientific landscape. One descope possibility not affecting dramatically the science (at the expense of telescope time) seems to be the reduction of IFU channels. We believe this will significantly reduce cost and complexity. Staged implementation might not be very cost effective but should be carefully investigated during the preliminary design phase.

The project has adequately defined the objectives and task plan for the next design phase. More emphasis should be given to Systems Engineering activities and a comprehensive Assembly Integration and Testing plan. There is also a significant risk associated with decoupling instruments from the NGAO design activities. The review panel recommends proceeding with the Preliminary Design phase because of the appealing science cases of NGAO and time constrains of the competition. However, we recommend using the first 6 months of the Preliminary Design phase to investigate descope possibilities and phased implementation aiming at reducing NGAO complexity, cost and risk to an affordable level possibly validated by an internal delta review.

5. Question 1: NGAO Science cases

Question 1: Assess the impact of the science cases in terms of the competitive scientific landscape in which the system will be deployed.

The NGAO team has presented a broad suite of science cases that are exciting and, if executed, will have large significant impact. On the timescale that NGAO will be deployed, JWST and ALMA are likely to be in operation and the next generations of large ground-based telescopes such as TMT are likely to be coming on-line soon thereafter. By focusing on high Strehl ratio science with MOAO, NGAO will be very complementary to these facilities.

Keck NGAO is the only large ground based facility to currently focus its future AO efforts on MOAO. Others will focus on either extreme AO systems, which will produce extremely high contrast narrow-field images on very bright targets, and/or wide field AO with either MCAO or GLAO, which provide uniform wide field, but low Strehl, corrections. By focusing on MOAO instead of MCAO, it is also likely to be the first large ground-based telescope to achieve both high Strehl ratios over a significant fraction of the sky and to provide a stable image for astrometry programs. When successfully implemented, NGAO will therefore be unique in its ability to provide high angular resolution, high Strehl ratio data sets, among 8-10 meter class ground-based telescope, and thereby continue its important leadership in AO.

Compared to the next generation of large ground based telescopes, NGAO will have higher background and lower sensitivity due to the smaller telescope. Nonetheless, it will also be an important technology precursor for these next generations of large telescopes; currently these telescopes are focusing on different first generation of AO systems (MCAO system for TMT, GLAO for GMT, and still under study for the E-ELT). NGAO may therefore provide AO instrumentation capabilities not covered by these systems.

As currently planned, the future space telescope, JWST, is a 6 meter telescope that will deliver images and slit spectra that are Nyquist sampled from 2.4 – 5 microns and sampled at 0.”1 resolution from 0.6 – 2.4 microns. The WMKO NGAO program has a very significant advantages over JWST by providing 2-3 times higher spatial resolution and 2-d spectroscopic imaging capability, albeit with higher background and reduced sensitivity. With a larger primary mirror, Keck NGAO will deliver higher angular resolution measurements at all wavelengths covered by JWST, but with the largest potential differences at wavelengths shorter than 2.4 microns. However, JWST obviously gains for large field science where the small PSF can be maintained over the full FOV. Therefore the largest unknown in understanding the possible strength of NGAO compared to JWST at short wavelengths for the science cases without directly measured PSF will be PSF knowledge (see below; this issue becomes increasingly important as one goes to shorter wavelengths). This is much less of an issue for the point source science cases or those special case extended targets with nearby point sources. Nonetheless, an IFU capability (two-dimensions) with NGAO at all wavelengths will be an important strength over JWST’s one dimensional slit spectroscopy. To take full advantage of the angular resolution gain over JWST it will be necessary to offer a spaxel scale that Nyquist samples the point spread function.

ALMA will be another important component of the scientific landscape when NGAO comes on line. Because this facility probes much longer wavelengths than NGAO, it will be purely complementary. With an angular resolution of 0.1”, which is a huge step forward compared to other radio interferometers, ALMA is well matched to NGAO. Keck NGAO and ALMA will both provide full 2-d spectroscopic imaging at subarcsec scales: NGAO probing the stellar populations and high excitation ISM (HII and H2), ALMA probing the cold molecular gas and dust. This will be particularly beneficial for studies of spatially resolved galaxy kinematics as well as protostellar and debris disks around young stellar objects. These facilities used in complimentary observations should enable fundamentally new capability for early universe galaxy assembly research and observations of star and planetary formation in our Galaxy.

The majority of the high impact science cases presented are enabled by the high Strehl, narrow field capabilities - these include the Galactic center studies, detection and imaging of the companions/planets of low mass stars and brown dwarfs, studies of the central black hole stellar environments in nearby AGN & QSOs. This narrow field AO also enables detailed spatial and kinematic imaging of high-z galaxies in the epoch of galaxy assembly. This broad spectrum of forefront science clearly justifies the Keck NGAO development. (We note that not all science areas have been as thoroughly developed. For the PDR, those which are less complete should be brought up to achieve a uniformly high level. Two areas which are apparently omitted and might deserve some development were crowded field stellar populations and AGN, specifically the accretion disk, obscuring torrus and inner jets.)

The major driver for wide field science is apparently the high-z galaxy studies -- here, the wide field capability provides increased efficiency (with the ability to study 6 galaxies simultaneously rather than one) but not a fundamental new capability. (The wide field specification is also necessary for correction of multiple guide star and higher sky coverage). However, if the inclusion of multiple deployable IFUs becomes a major difficulty in cost, schedule, complexity and uncertainty for the NGAO project, this incremental efficiency gain from multiple IFUs needs to be more thoroughly justified.

6. Question 2: Science & technical requirements

Question 2: Assess the maturity of the science cases & science requirements & the completeness & consistency of the technical requirements

The science cases are impressively well developed, with clear and explicit science requirements. Dividing the science into “Key Science Drivers” and “Other Science Drivers” was a helpful device for understanding which science cases drive the technical capabilities of the NGAO system and which give the system scientific breadth. There has clearly been a tremendous amount of work done to translate these scientific requirements into the system-level technical requirements and it represents a good understanding for this stage of the project. The system-level technical requirements have been used to develop a further set of subsystem and component-level requirements. These are self-consistent and generally complete at the Conceptual Design level

Among the open technical requirements that will be important to understand soon are the Point Spread Function (PSF) requirements. For some of the science cases (predominantly the extra-galactic science cases) that do not contain simultaneous measurement of a point source, this represents a significant technological risk. There may be significant scientific gains for science programs involving anything that is dusty, young or old from considering L’ imaging, as the AO performance should be improved at these longer wavelengths and a cooled AO system will trump all the work that has been done with existing AO systems. Due to choices of dichroics, it has been designed out of the first generation TMT system and therefore would expand the uniqueness of the NGAO system.

A second open requirement (at the subsystem level) is the necessary laser power. The current power requirements may only be correct for the case of a circularly polarized (dual wavelength) laser propagating along the earth’s magnetic field lines in one particular direction on the sky, and were computed for the case of median sodium column density. More work is needed to (a) assess the expected photon return vs. laser power at zenith for a range of different sodium column densities, and (b) double-check the existing results on the relationship between photon return and the LGS WFS measurement error due to noise.

One need for the next phase of this project is the development of a comprehensive simulation tool to fully evaluate system performance vs. critical system parameters for each science area. This tool should include the expected instrument sensitivities and uniformity, the expected PSF and Strehl, and very importantly – the inclusion of time variable effects such as jitter and seeing.

7. Question 3: NGAO conceptual design & feasibility

Question 3: Evaluate the conceptual design for technical feasibility & risk, & assess how well it meets the scientific & technical requirements

Yes, the performance of NGAO is predicted to meet its scientific and technical requirements, according to the extensive range of AO analysis and simulation studies performed by the NGAO design team. These studies confirm that the lower-level requirements developed for the NGAO subsystems have been consistently derived from the overall system-level performance requirements, and that the latter will be met if the NGAO subsystems perform according to plan.

However, many of these subsystem requirements are challenging extrapolations of the best results that have been achieved today with any operational AO hardware. The NGAO team can identify highly encouraging demonstrations in many if not all of these cases, but more work is needed to validate these results and obtain similar levels of performance from reliable, observatory-class components. Some of the requirements in these categories include:

- The value for the return signal from the sodium layer used to compute LGS WFS performance is optimistic. These numbers assume optical pumping (circular polarization) and two-frequency operation to recover atoms in the 2b ground state and are based on published data from the SOR. Since Mauna Kea is further from the magnetic pole than the SOR, there will be a significant reduction in this signal level. Also, it is not clear what the acquisition/development plan is to obtain a two frequency laser. Recommendation: take a careful look at what is realistic in terms of the return signal. Compare Keck NGAO estimates with what TMT has done recently (they are now using ~one-half of their original return values).
- The AO system performance relies critically on LGS wavefront sensor and near-IR tip tilt sensors that have not yet been demonstrated in terms of read out noise at the required frame rates. These sensors need to have been tested to the required performance by the end of the PD phase.
- The performance assumes that the open loop operation of the MOAO MEMs mirrors can achieve the assumed residual errors. This is a high risk area since these elements need to be calibrated for non-common path aberrations for every position in the wide field path, and corrected for non-linear response and gain effects in the device and accommodate any additional effects caused by the fact that the light is fed to the MEMs device from a moving mirror somewhere on an articulating arm, introducing the very likely possibility of registration errors between the wavefront sensor and the elements being controlled.
- 32x32 and 64x64 MEMS with large (4 micron) stroke, calibration errors on the order of 30 nm, and few or no dead actuators.

Although NGAO has a 6-year schedule, the expected performance of these components should be sufficiently well known at the end of the preliminary design phase (24 months from now) to allow long-lead items to be purchased (Lasers, MEMs, large optics, detectors, tip-tilt mount). Although it is true that overall NGAO performance will degrade gracefully if some or all of these components under-perform, breakpoints exist where simpler and cheaper design concepts become the preferred approach because they will perform at least as well for less cost and at less risk.

- *If the predicted performance of the conceptual design does not meet the scientific or technical requirements are there adequate plans for addressing these deficiencies as the project continues?*

Generally speaking, the System Design Phase has not yet developed detailed development plans or backup options if the elements of the conceptual design do no perform as planned. As with (admittedly) many other AO projects, the NGAO project is depending upon external R & D funding sources and nearer-term AO systems to develop the technology they intend to use. For example, here is one element from the project's technical risk register:

Adequate wavefront sensor CCDs not available	Fast low-noise high pixel count (256x256) detectors required. A CCID-56 with more pixels is a prime candidate. CCID-56d (160x160 pixels) devices are available, and being tested for GPI.	1) Monitor the progress of the AODP-funded CCID-56 project.2) Evaluate alternative options.

The NGAO project needs to coordinate very closely with all of these external activities to avoid being surprised by schedule slips or performance shortfalls. It should obtain "ownership" of its top 1-2 technology development requirements if at all possible.

Fallback options should also be further developed as part of the plans for addressing possible deficiencies. Are there intermediate designs (with interesting levels of performance and growth potential towards the current concept) that could be implemented if the current laser, detector, MEMS, or MOAO requirements cannot be met within the desired schedule or available budget?

Detailing the implementation of a MCAO option is one recommended fallback option, since (i) the cost is understood and relatively modest, (ii) the technology is available, (iii) successful on-sky demonstrations of MCAO on 8-10m class telescopes have already occurred, (iv) MCAO will provide some improvements in sky coverage and wide-field AO performance if MEMS and MOAO take longer to implement than currently envisioned, and (v) MCAO will reduce the stroke and linearity requirements on the 9 MEMS to be implemented in the dIFUs and the LO NGS WFSs.

How to define a fallback option for high Strehl, short wavelength AO may be more challenging. But reducing the number of (still very bright) laser guide stars to a minimum and driving the 64x64 MEMS in closed loop (in the current woofer/tweeter mode) may be one possible approach. Other 64x64 wavefront correctors with a modestly larger inter-actuator pitch could be considered in this case, if necessary, to increase the FoV to 30-40 arc seconds (for the LGS asterism) with acceptable pupil distortion.

We would recommend a more pro-active stance in the development of subsystem components (especially detectors and lasers) during the preliminary design phase of the project.

o *Does the conceptual design appear feasible?*

No fundamental showstoppers have been identified, but the design depends upon highly advanced AO component technology, and is more complex and sophisticated than any AO system which has passed beyond the design phase to date. As with any new AO system concept, achieving the performance

requirements at both the subsystem and system level is very likely to be an incremental process. The project's schedule and AIT/commissioning plan should avoid attempting to implement too much, too quickly. To repeat, the conceptual design is very complex. It is probably feasible to implement this design eventually, but likely not within the estimated schedule and budget presented.
Our main concerns are already known by the NGAO team but bear repetition here: 6 channels of MOAO using 32x32 MEMs devices operating in open loop, adequate signal from the sodium layer for 64x64 wavefront sensing, low noise performance of the detector arrays for both LGS wavefront sensing and TT sensing in the near IR. While preliminary demonstrations of open loop control of MEMs on the sky are encouraging, it was done at a much lower scale (140 elements vs. 1000 or 4000) and needs to be followed full scale lab and on-sky demonstrations to measure residual errors.

- *Is the risk identification complete, and if not, what additional risks should be considered?*

We cannot find MOAO performance listed as a risk, unless it is considered as a subset of "wavefront error budget not met due to invalid assumptions." The open loop control issues in MOAO include the correction of non-common path errors and the maintenance of DM-to-WFS pupil registration, not just the linearity of the DM and the WFS themselves. Current demonstrations with 12x12 MEMS need to be scaled up to order 32x32 to demonstrate that MOAO calibration errors still remain in the 50-60 nm RMS range. We also recommend a careful examination of the error budget associated with details of the NGAO MOAO design concept, and a risk mitigation plan that demonstrates required performance in the lab of a prototype channel of the MOAO design.

- *Are the risk mitigation efforts and future plans for risk mitigation likely to result in retirement of all critical risks?*

Eventually yes, but this is not likely to happen within the current NGAO schedule if the past experience of the AO community is any guide. Once again, the designs and performance characteristics of the critical AO hardware components should be known by the end of the Preliminary Design Phase to enable long lead procurement to begin.

We recommend developing a detailed risk mitigation plan (that builds on the mitigation column in KAON 510 and 566) to show in a waterfall fashion the expected reduction of risk with time to an acceptable level at each major milestone.

8. Question 4: Schedule & Budget

Question 4: Assess whether the design can be implemented within the proposed schedule and budget.

The proposed schedule and budget estimate have been carried out with sound methodology (R Dekany's book). However, they do not yet represent a realistic estimate. Some thumbing through the budget book showed some pages not complete or no estimates for the words in the tasks – a detailed review and audit should be conducted – unless this has already been done. The panel feels that both are success oriented and we recommend that during the PD phase both the cost estimate and schedule be further refined to more conservatively reflect the challenge of implementing the NGAO system. The cost estimate should become a confident basis for budgeting the project. The contingency estimate presented is too lean and should be refined to fully reflect the technical and market risks inherent in the system. The schedule should be refined to more fully reflect the numerous procurement, technical, integration and commissioning risks in such a challenging system:

- 22 months to complete a preliminary design is realistic
- +24 months to complete the detailed design is realistic
- +18 months for Subsystem development and testing – the laser system needs more time than this and needs to be started much earlier [is some level of development planned to begin in 2009?]
- + ~3 months of lab integration and testing – is too short a time before the system is moved to the summit
- +6 months of telescope integration – is too short by as much as a factor of two.

The methodology used in the SD phase is a sound means of developing a cost estimate and is a good basis for this further refinement. The Basis of Estimate details are consistent with what is required of a project like NGAO.

The contingency for the laser system development at 18% is probably not adequate. Based on guidelines from TMT's process and the state of development for what is assumed about the laser return, this number should be of the order of 30% or even more.

9. Question 5: Management and risk mitigation

Question 5: Evaluate the suitability & effectiveness of the project management, organization, decision making & risk mitigation approaches, with an emphasis on the next project phase (preliminary design) and also with respect to the entire project.

The Executive Panel project management arrangement has worked well during the SD phase, building team trust and consensus and facilitating a considerable system design effort. For the PD phase, the NGAO team proposes an overall project manager with separate project managers for each of the 3 institutions. The level 2 PM's are responsible for their institution's individual deliverables. This arrangement is intended to promote institutional focus while not obscuring the imperative to deliver. This arrangement may succeed well for the PD phase; however, for the Detailed Design phase and subsequent phases, we recommend the following revisions to the NGAO WBS, org chart and project management arrangement.

The WBS should be organized strictly along the lines of deliverables with the DD phase and subsequent phases accommodated under these deliverables. Thus, the Level 2 WBS elements should be Project Management (with System Engineering under PM as a Level 3 element), each of the subsystems (AO, Laser, etc. taken through Lab Integration), System Integration, Transition to Operations.

- System Engineering is a technical staff function reporting to the PM who holds system responsibility.
- The organization chart should have managers responsible for each of these Level 2 and then Level 3 elements.
- There should be a single Project Manager to whom all Level 2 managers report and who chairs the CCB (which is advisory to the PM).
- The CCB process should be defined into hierarchies of decision levels corresponding to WBS levels, and budget and schedule changes as well as interface changes. This hierarchy should define decision authorities.

This reorganization will better accommodate the separate and asynchronous phasing of different WBS elements under a likely funding-paced project.

10. Question 6: NGAO overall strategy

Question 6: Provide feedback on whether the overall strategy will optimize the delivery of new science.

Given the fact that each of the major new facilities contemplated for the next decade is directed at many of the same major science areas (e.g. early universe galaxy assembly, star and planetary formation and AGN environments), the first operational facilities will have the best opportunity to make the major strides in understanding – with the later facilities providing more comprehensive but perhaps not as exciting results. It is therefore imperative the NGAO be sufficiently realistic to avoid major schedule slippage or lost capability. We strongly advise that a more predictable, phased implementation approach be developed and adopted in the Preliminary Design phase.

NGAO is currently planned with a long design phase and one-shot simultaneous implementation with a less than 1.5 yr duration (2013+). This overall strategy is predicated on the assumption that a thorough design effort will clearly identify and resolve all uncertainties so that procurement and implementation can occur straight forwardly with predictable outcome. An alternative approach would be a phased development and implementation - to spread out the implementation and testing. This longer period of procurement, integration and testing could provide more efficient use of key technical personnel. In addition, the staged approach would provide continuous upgrade capability to WMKO -- providing more immediate science return. One example of this is the cooled AO enclosure which would immediately benefit the current capabilities- assuming the existing AO is made to operate in the cooled environment. A second example is the high power lasers - these devices have major procurement/vendor uncertainties which could be usefully explored with an early implementation strategy and if success is achieved early, one of the lasers could greatly benefit the existing system.

11. Question 7: NGAO readiness toward Preliminary Design

Question 7: Gauge the readiness of the project to proceed to the preliminary design phase

The project team has developed a sound management plan and has adequately defined the objectives for the preliminary design phase. The work breakdown structure seems a bit disorganized and inconsistent with what we heard briefed. In particular, the systems engineering normally reports to the program manager but is listed as a parallel, equal-footing task. We recommend reviewing the WBS and schedule associated with each element to make a more consistent picture. The technical design is very complex and will be difficult to implement. System engineering activities to accurately overview the design of the Adaptive Optics, multi-laser guide star facility and the interfacing/operation with the focal plane instruments should be increased. It is recommended to dedicate a full time system engineer already for the preliminary design phase. Detailed plan for the Assembly, Integration, Testing and Commissioning of the NGAO facility is essential to ensure that the NGAO design is compatible with the system testing approach and the list of tasks and amount of work to be performed is clearly identified.

The planned human resources dedicated to AIT and commissioning plan activities during the preliminary design phase is underestimated.

Apart from the comments above, the team selected for the preliminary design phase is well qualified and an adequate number of hours have been allocated for the tasks at hand.

The documentation for this project is excellent and more than adequate for a conceptual design.

There is also a significant risk associated to the decoupling of the instrument from the NGAO design activities. We recommend starting the conceptual design activities of the instrument and defining interfaces between NGAO and the focal plane instrument early in the NGAO preliminary design phase.

The panel feels that the project should be more proactive in controlling technical risk by funding development for the highest risk items. There appears to be no budget available for this purpose. We also feel that in some areas (laser development for instance) it would be useful to collaborate with other organizations (e.g. TMT) to develop a common set of requirements

The review panel recommends proceeding with the Preliminary design phase because of the appealing science cases of NGAO and time constrains of the competition. However, we recommend using the first 6 months of the preliminary design phase to investigate descope possibilities aiming at reducing NGAO complexity, cost and risks to an affordable level possibly validated by an internal delta review.

APPENDIX A
Review Panel Questions and NGAO Team Responses

Reviewer	RIX n	RIX typ	Doc nr	Ch.	Page	RIX text	Replier	RIX Reply
NS	1	RIQ			general	The main issue is: is there a phased plan for implementation? The entire plan is very aggressive and success oriented (in terms of raising funds) and technical feasibility. And can the entire plan be done before TMT (or JWST). There may well be a discussion of this in those documents I haven't yet had a chance to read so I apologize if that is the case. In any case, I would like to see a fair amount of discussion given to such a phased plan.	PW CM	For this Design Review we are addressing the full system design and implementation. As requested by the Directors and SSC we will address phasing and descope options during the Preliminary Design. We touch on the phased implementation topic briefly in section 4 of the Systems Engineering Management Plan and we quote from the start of this section: "This section was not identified as a System Design phase deliverable. Although the Directors and SSC have expressed interest in these topics we all agreed that this issue would have to wait until after the System Design Review. That being said we have had some initial thoughts on this subject especially during the development of the system architecture. These initial thoughts are provided below." We will determine whether we can have a fuller response prior to the review. Assuming funding availability we believe that NGAO can be implemented prior to TMT or JWST.
RQF	1	RIQ	575		19	Could the architecture shown on page 19 in Figure 8 be used to support MCAO at all, or are all the DMs always conjugate to the pupil? Fig 14 page 24 (same as in KAON 511 p 72) shows a "DM Projection" box in the data flow with a "DM conjugate altitude" implying that some of the DMs could be at altitudes other than the pupil.	PW	All of the DMs are conjugate to the pupil. However, one of the reasons that this wide field relay design was selected was that the fold mirror between the first OAP and the DM is conjugate to ~9 km. MCAO can therefore be either a backup approach or a future upgrade. This was also taken into account in the RTC design.
RQF	2	RIQ	575		general	Are there any science requirements that would be benefit significantly from MCAO?	CM	The science case that would benefit most from MCAO is resolved stellar populations in crowded fields. To compete with MCAO for this science case, MOAO's total well-corrected area provided by multiple deployable imager units would have to be a square arcmin or more. In confusion-limited fields the higher Strehl obtainable with MOAO might give a modest advantage over MCAO over smaller fields, but this would only be useful with good PSF knowledge. Three other science cases would potentially benefit from MCAO (black hole mass measurements in nearby AGNs, gravitational lensing by clusters, and imaging of Jupiter and Saturn), but for these science cases MOAO supplemented by other wide-field capabilities has a strong and perhaps unique science role to play because of its higher peak Strehl.
RQF	3	RIQ	575		20	It appears from Figure 9 that there are always 9 LGSs available to be positioned on the sky as: (1) a variable diameter pentagon, (2) one in the center, and (3) three point and shoot lasers that can be positioned anywhere in the 150" field. Is that correct?	PW	That is correct. The field passed to the LGS WFS is actually slightly larger, 174".
RQF	4	RIQ	575		19	Since the wide field relay always feeds the LGS WFSs , are all nine LGSs always used for tomographic reconstruction for closed loop control of the wide field AO relay DM? Or, are just 5 LGSs used for tomographic reconstruction? [I have just seen the discussion on p 115 ff of KAON 511 which partially answers this question.]	PW	We intend to have the flexibility to use all nine for tomography. In some cases the three point and shoot lasers may not provide significant additional information for tomography and may not be used for this purpose.
RQF	5	RIQ	575		19	I presume the statement in the second paragraph, "High order refers to three times the DM actuator spacing of the low order DM" was meant to imply the actuator DENSITY is three times as high in the high order AO relay? (~60 vs 20 actuators across the pupil?)	PW	Yes, the narrow field relay DM has 64x64 actuators.
RQF	6	RIQ	575		19	Based on the diagram in Figure 8, and the description in the Sysem Overview on pages 17 and 18, it appears the low order AO DM operates in a closed loop mode in which measured error signals from the LGS WFSs are minimized by an algorithm of the control system. Is it correct that the the final correction for the narrow field science instruments in LGS mode is an open loop correction with drive signals to a 64x64 MEMS device derived from a tomographic reconstruction using the 5 LGSs formed by the pentagon and center beacons?	PW	Yes, your interpretation is correct for LGS mode. In some cases all 9 LGS beacons will be used for the tomographic reconstruction.
RQF	7	RIQ	575		19	Are there only two DMs in the optical path to the narrow field science instruments -- the low order wide field AO relay conventional DM and the high order narrow field AO relay MEMS DM? That is, there are no additional MEMS devices in this path to further correct an even smaller field in and around the target?	PW	Yes, there are only two DMs in the path to the narrow field science instruments.
RQF	8	RIQ	575		19	In NGS operation, does the architecture support controlling both the low order wide field AO relay DM and the narrow field AO relay MEMS in closed loop mode?	PW	Yes.
RQF	9	RIQ	575		19	Related to my question #8, how is the wide field AO relay DM controlled during NGS operations?	PW	Two options need to be evaluated. One would be to simply flatten or sharpen (to minimize static aberrations) the wide field DM. The other, and preferred, approach is to apply the low spatial frequency aberrations, perhaps at lower bandwidth, to the wide field DM, and apply everything else to the narrow field MEMS DM.
RQF	10	RIQ	575		19	What sensors are used to control TT during NGS AO operations?	PW	The NGS WFS provides both high order and TT control.

RQF	11	RIQ	511		62	Is there a block diagram in the reference material showing the control architecture for the operation mode for each science instrument for the detectors and mirrors listed on page 62? For example, I count as many as 11 TT mirrors when the d-IFS is in use. Where can I find the control block diagram showing how the output of the detectors (TT sensors and WFSs) are connected to the mirrors (TT mirrors, DMs)?	PW	We do not have such a diagram yet. We will discuss whether we can produce this diagram prior to the review. Your TT mirror count is correct.
RQF	12	RIQ	549		19	Where is the LOWFS assembly (TT sensors ad TTFA shown as Figure 12 on page 20 of KAON 511) in Figure 1 pg 19, KAON 549? It would seem this assembly belongs in the vicinity of the the box labeled acquisition camera in this figure?	PW CM	The LOWFS assembly is located at the d-IFS location. Ideally we would integrate the LOWFS and d-IFS packaging, and they would be delivered together. The presented LOWFS assembly design is intended to be an interim design solution which may need to be implemented if the combined package cannot be delivered on the required schedule.
RQF	13	RIQ	511		19	In Table 3 the main WFS detector requirements are listed. Are the CCID-56 arrays (ref p 27) for the LGS WFSs the JFET devices built by MIT/LL? Do you have measured data on the read noise at 3e and 2kHz or is this a projected performance number?	SA	The reference to the CCID-56 on page 27 does refer to the existing 160 x 160 pixel devices with a planar JFET single stage output structure (CCID-56b). Read noise of ~1e- has been measured at 1MHz pixel clock rates with these devices. For the NGAO LGS WFSs a larger device (256 x 256) is required, and achieving a 2KHz frame rate with the larger device would require ~3.5MHz pixel clock rates. This will require a 2 stage amplifier, such as that implemented on a recent variant of the CCID-56, called the CCID-66 which uses a planar JFET as the first stage, and a conventional MOSFET as the second stage to support higher pixel clock rates at the expense of an increase in read noise. Test data from these devices is not yet available, but based on appropriate mathematical extrapolation from the performance of the CCID-56 the figure of 3e- at a 2HKz frame rate appears sufficiently conservative.
RQF	14	RIQ	511		27	What is the status of the radial CCD arrays being developed to accommodate sodium LGS elongation? Is that program just not far enough along to be in the running for the LGS WFS for NGAO?	SA	The polar coordinate (radial) detector design is completed and we are awaiting the start of the wafer run to fabricate the prototype devices. This development has been aimed at telescopes of ~30m aperture where perspective elongation of the LGS image is a significant effect. If detectors of this type were required for NGAO they could probably be available on an appropriate timescale. However, since NGAO plans to use center projection the amount of elongation due to the maximum offset of <5m is not significant compared to the impact of other aberrations on the LGS image, so it does not seem necessary to employ the polar coordinate detector for NGAO.
RQF	15	RIQ	511		27	How well do the elongated spots at the edge of the aperture fit within a subpaerture of 4x4 pixels on the 256x256 array? What signal-to-noise do you expect from the laser guidestars for this size subaperture?	VV RD	The LGS spot size is calculated on p. 15 of KAON 551. The result is 1.9" for the worse case elongation at the edge of the telescope aperture (substituting the max elongation value into the calculation on p. 15). The subaperture diameter for the LGS HOWFS is 4 pixel x 1.45"/pixel = 5.8" on a side, so even the most elongated spot fits comfortably with minimal field stop losses. The spot diagrams versus 4x4 pixel subapertures for the optical design of the LGS HOWFS alone are shown in Figures 9 and 10 of KAON 551 and are seen to be quite good. There is an outstanding issue of the optical quality delivered by the WF AO relay that was addressed in another review question. The signal-to-noise calculation is complex, but for one example, the Galaxy/Galaxy Lensing science case (w/ the baseline 100W into total of 6 beacons architecture), we typically see average LGS spot size of 1.7" and SNR's of ~30 during a -3db control time (~1,000 Hz WFS rate), resulting in a 1-D centroid error of about 0.07 arcsec (rms) [Hardy 5.15], which in turn leads to ~60 nm rms high-order measurement error.
RQF	16	RIQ	511		27	Is there an existence proof for the 256x256 IR focal plane array with 7 electrons of read noise at 500 Hz frame rate? If so, who makes it and how long has it been available?	RD VV	Table 3 in KAON 511 (based on Table 10 of KAON 551) erroneously states our TWFS IR detector requirements as 7e- at 0.01-200 Hz for a 240x240 pixel readout. The text in KAON 551 states the max read rate is 10 Hz and the total number of pixels that need to be read is 5 x 5 subapertures times 2 x 2 pixels = 100 pixels using multiple ROI on the IR array. This will be corrected in the documentation. The TT and TTFA sensors need to read faster, but use fewer pixels. Noise measurements made on a H2RG at Caltech show that a read noise of 3.5 e- can be obtained when reading out 12 pixel using Fowler 8 sampling at an equivalent ROI rate of 490 fps. Both the TT/TTFA and the IR WF TWFS specifications are extrapolations of this data. More detail on our results can be found at: http://www.oir.caltech.edu/twiki_oir/pub/Palomar/Palm3000/P3KWFS/P3K_WFS_meeting_2.ppt though we have not yet had time to write up these results properly. In general, Slide 6 shows the measured noise plot. These results will need to be interpreted more directly in terms of use cases for an IR LOWFS.

RQF	17	RIQ	551			So, let me see if I have this right. (Sorry for the simple minded questions on architecture -- still trying to understand it). LGS mode: Lenslet arrays in the 9 LGS WFSs are selected to sample the pupil at either 16, 32, or 64 subapertures across the diameter. The two TT and one TTFA sensors in the wide field relay path collect data from 3 NGS targets in the field. The TWFS in the narrow field relay path is used to update the LGS WFSs calibration (this means a dichroic from the bank is inserted) -- or could the TTFA sensor be used for this function? The Tip-Tilt stage of DM1 (the wide field AO relay DM) is adjusted in a closed loop servo and the Tip-Tilt stage for DM2 (the 64x64 MEMS DM in the narrow field AO relay) is commanded open loop? (don't see a track sensor in the narrow field path other than the NGS WFS?) The RTC engine iterates on a tomographic solution and provides commands to the MEMS DM and DM1. DM1 is fixed at 20 actuators across the pupil and is somehow operating closed loop since it is in the path to the LGS WFSs? DM2 is commanded open loop.	PW	Your summary is correct for LGS mode and narrow field science. For wide field science the sensors and MEMS in the narrow field relay are not used. There is a TWFS sharing light with the TTFA that provides updates to the LGS WFS calibration. Ideally we would only need and use the tip-tilt stage for DM1 even for narrow field science. However, until we better understand the dynamics for this tip-tilt stage we have included a tip-tilt stage for the narrow field MEMS DM, which presumably could have higher bandwidth performance due to its much smaller size. This MEMS DM tip-tilt stage would also provide the best performance for NGS mode where it could be operated closed loop.
RQF	18	RIC	553			A few simple block diagrams showing input signals to a controller and output signals to DMs and T-T stages would help clear up some of my confusion. The information may be in the documentation, but it is either not in enough detail or too much detail. I think such a set of diagrams would be beneficial at the meeting to insure we don't get bogged down in misunderstanding each other when discussing architecture and operating mode issues.	PW	Thanks for the suggestion. We plan to have some diagrams for the SDR.
BLE	1	RIC	3	4.2.2	119	150W of required laser power seems inadequate to obtained the indicated RMS WFEs due to noise with up to 9 beacons, 17 cm subapertures, and up to 2000 Hz frame rates. Further description of this simulation/analysis is requested. Order 64x64 wavefront sensing/correction drives the complexity of many other systems, and should not be specified unless it is realistic.	RD PW	True, but this combination of parameters is not an optimal performance point. Assuming 150 photons/cm2/s/W (the SOR return) and an r0 of 14.7 cm at 30 deg zenith angle, the optimal is 64x64 sensing at 1050 Hz (for half this Na return the optimal would be 58x58 sensing at 908 Hz. A study on the effect of segment figure errors was documented in KAON 469. As a result 64x64 wavefront correction was selected to reduce the telescope static aberrations to 43 nm rms; this error would be 59 and 66 nm respectively with 32x32 and 20x20 correction. The wavefront sensors also have 32x32 and 16x16 subaperture options. The 64x64 option is required to meet the highest narrow field science performance requirements, and is especially optimal for bright NGS wavefront sensing where the atmospheric fitting error can be further reduced without paying a measurement error penalty. With a 64x64 MEMS (an early version has just been delivered to the LAO) the static telescope aberrations can be corrected (once sampled) even if 32x32 wavefront sensing is being performed. 64x64 also provides a large dark hole and fine control of residual PSF speckles for high contrast observations with a coronagraph.
BLE	2	RIQ	3	Table 3	19	Has an intensified EBCCD been considered as an alternative detector for the low-order IR NGS WFS?	RD/PW	It has been discussed & we will consider this option. Note that COO is working with HIA/TMT on the same IR NGS WFS issue for IRIS, including this detector option, and the results will be fed back to our project.
BLE	3	RIQ	3	Fig 13	20	What is the requirement on probe arm positioning stability and repeatability in an open-loop MOAO system, where both MEMs and WFSs are patrolling a field? How has this requirement been factored into the probe arm design? Clarification: Do you have a requirement for the DM-to-WFS pupil registration as a fraction of the pupil diameter, and can this be used to derive requirements on the probe arm positioning tolerances?	PW	The probe arm requirements flow directly from the science image positioning accuracy and knowledge requirements and are summarized in Table 2 of KAON 562: acquisition accuracy = 40 mas (30 um), stability = 1.4 mas and positioning knowledge = 1 um. These requirements can readily be met by off-the-shelf rotary mechanisms. Note that these requirements are small compared to the ~ 340 um MEMS element size. The input to the probe arms is telecentric so no tilt is required versus off-axis position. The biggest risk to pupil registration could be in rotation, but this should be small and is calibratible versus field position.
BLE	4	RIC	3	Table 6	31	The very large wavefront errors in the LGS WFS optical path would seem to be a concern for an open-loop MOAO system.	PW	We agree & recognize that the current optical design for the input to the LGS WFS has inadequate performance. We plan to develop a better design during the preliminary design. There is no fundamental reason that an acceptable design cannot be developed (for example, an Alverez style corrector plate was suggested or a 2nd OAP can be used).

BLE	5	RIQ	3	Fig 33	43	Can a separate quarter wave plate be inserted in each beamline without interference at the indicated location?	PW	Potentially. However, if needed this might be more practical to implement earlier in the beam train.
BLE	6	RIC	3	`3.4.1.2	44	The idea of using a telescoping tube to transfer the laser beams to the telescope elevation structure at some location _other_ than the elevation axis may not be very practical	PW RD CN	Our first preference would be to have the lasers on the elevation moving part of the telescope or to use fibers. The elevation axis would of course be next on the preferred list, however this would not be easily achieved without a significant operational impact on instrument changes and reduction in backup capabilities (with an instrument on the other Nasmyth platform). We therefore feel that it is necessary to investigate some form of changing baffling to contain the laser light. Note that a non-elevation axis re-pointing system is used with the Palomar laser transport that relies on a mirror moving on a trolley. Also the Keck Interferometer uses an off-Azimuth-axis Coude tracking system. Baffling is the main issue in such a system. As a backup we could get rid of the telescoping baffle tube if we made the dome a class IV laser enclosure during laser operation.
BLE	7	RIQ	553/3	All/3.5.3	All/71	How is the low-order NGS WFS data blended with the LGS WFS measurements in the tomographic wavefront reconstruction?	DG	Low order blind modes are rejected from the tomographic reconstruction and are replaced with these modes from the low-order NGS WFS results. We understand that this is the same approach as TMT plans to use.
BLE	8	RIQ	3	4.1	113	The throughput penalties, optical system complexity, and costs associated with developing a single AO system for both narrow- and wide-field modes appear to be significant. Has developing an AO system for just one of these applications been considered as a possible descope option?	PW	We have not considered the descope option of only building a narrow field or a wide field system. Four of the five key science drivers and 8 of the 13 science drivers only require narrow fields. However, in order to get good sky coverage for most of these science cases we still need a wide field for the tip/tilt stars. As you point out there is a throughput penalty and additional optical system complexity. The transmission to the science instrument is 0.74 for the wide field and 0.65 for the narrow field. The narrow field has 12 reflections & 14 transmissions versus 7 reflections and 10 transmissions for the wide field. Developing separate systems for the narrow field and wide field science was considered as part of our evaluation and downselect of 5 different architectures (KAON 499). We concluded, for a number of reasons including cost, that this split relay architecture was ranked lower than the selected cascaded relay architecture. We also considered a large relay architecture that did not require a separate narrow field relay and this architecture was also ranked lower. We rejected the idea of two separate AO systems for these purpose at different locations because of competition for space at other foci and because of the cost of duplicating much of the infrastructure.
BLE	9	RIQ	6	Fig. 1	2	What management and communication structures are in place to promote communication and coordination between the COO, UCOLICK, and WMKO arms of the project? Is this the organization structure used during the system design phase? If so, how has it worked?	PW	The proposed organization structure is a modification to the org structure used during the system design phase with most of the same participants. The modifications distribute responsibilities between the leads at the three Observatories (the system design phase structure had more shared responsibility). Similarly the work has been packaged for more independence at the three Observatories than there was during the system design. We found that we worked well together during the system design and the changes are intended to improve efficiency. Communications are discussed in section 3.10 of the referenced document (KAON 574). Good working relationships already exist within this team and communications are only a phone call or email away. We will have monthly team videoconferences and bi-weekly management telecons. Materials will continue to be shared through the Twiki site.
BLE	10	RIC	6	Tab. 12	20	The discrepancy between TMT and NGAO cost estimates for the LGSF should be discussed further. Clarification: I was really thinking about the laser systems costs, not the rest of the LGSF.	SA	The laser system cost estimate prepared for NGAO is based on significant understanding of the cost of such systems gained during the development of the laser systems for the Gemini South Observatory and the Keck I telescope. The estimated cost for two 50 W lasers of $7.3M with contingency assumes that the required lasers can be produced under reasonable commercial/industrial conditions and will not require paying aerospace labor rates and overheads. If our comparison details are correct the TMT estimate indicates that two 50 W lasers were ROM quoted by an aerospace vendor with 28% contingency at $13.6M. The figure used for NGAO includes contigency of 18%.
BLE	11	RIQ	427	All	All	Did these performance tradeoffs for fixed vs variable asterism geometries use the error budget tools described in KAON 471, or some other approach?	PW RF	The variable vs fixed LGS asterism trade study in KAON 427 did use the error budget tool. A more detailed simulation/analysis of LGS asterism geometry and size was performed (KAON 429) using a numerical IDL based MCAO simulation tool.

BLE	12	RIQ	452/3	ll/4.2.	All/116	The MOAO/MCAO trade study is not adequately quantified in terms of many of the metrics presented in the review documentation. MCAO should be considered further, particularly if (i) The fold mirror immediately following OAP1 is located at an appropriate conjugate and (ii) order 64x64 wavefront correction is not practical due to the laser power requirements. What is the overall impact on the wavefront error budget if the increased DM projection error for MCAO is traded against the implementation errors associated with open-loop wavefront sensing and correction in MOAO?	PW DG	An MOAO/MCAO trade study was documented in KAON 452. Our early downselect to MOAO resulted in our not quantitatively evaluating MCAO beyond what was done in this KAON (& to a lesser extent in KAON 499). The MCAO generalized anisoplanatism wavefront error and MOAO anisoplanatic error were quantified versus field angle in Figures 8 and 9 of KAON 452, respectively. The drastic reduction of generalized anisoplanatic error was seen as a major advantage for MOAO (~40 nm over the field versus > 100 nm for reasonable fields). Whether MOAO can achieve the 40 nm we have budgeted for its unique errors remains to be demonstrated, but lab results to date are encouraging. The fold mirror is conjugate to ~ 9 km and was one of the reasons this design was selected (in order to provide an alternate future path). As discussed in response to Brent's question 1 we do feel that 64x64 is practical and necessary. The overall impact on the wavefront error budget if MOAO were just turned off would be that the wavefront error would grow by ~ 100 nm in quadrature from 170 nm to 195 nm; this is still less than the MCAO generalized anisoplanatism error. The metrics introduced in KAON 452 were presented as a suggested approach at the time (January 2007). These were not adopted later as a process by which we would make the architecture decision. Instead we used a multiple criterion scoring system explained in KAON 499, summarized in the table in Figure 6 of that document. Considerations there included technical performance, risks, operations/development costs, expandability, and compatibility with phased implementation. The benefits of MOAO are pretty clear from KAON 452 Figure 8. The NGAO science cases require significantly reducing the generalized anisoplanatism
BLE	13	RIQ	452/2	All	All	What is the impact of the above performance variations on the viability of the science case?	CM	We have already included our best estimates of MOAO implementation errors in our performance analysis. The quoted NGAO wavefront errors, Strehl, and enclosed energy take into account all of these implementation errors, and meet our science requirements. As we learn more about MOAO implementation from the VILLAGES experiment at Lick, we will update our estimates for these errors. To date the VILLAGES measurements are quite consistent with our error budgets.
BLE	14	RIQ	452/4	All	All	What is the impact of the MCAO/MOAO tradeoff on the technical risk assessement matrix?	RD PW CM DG	With reference to first 10 risk items in the table in KAON 510: Item 1 PSF calibration. Over small fields of view, Britton has shown excellent PSF calibration extrapolating from a single on-axis PSF, corresponding to the MOAO case. MCAO results from MAD show quite uniform PSF correction, but we are unaware of the astrometric and photometric limits in that data. The situation differs for crowded vs. sparse vs. confusion limited fields. We will monitor Gemini S MCAO progress to understand the limits of MCAO photometric and astrometric precision. Item 2 sky coverage. MOAO is expected to provide more highly sharpened TT stars for better sky coverage, at somewhat higher technical risk. Item 3 Lasers. We believe MOAO sharpening of the TT stars can reduce laser risk compared to MCAO, because the TT sharpening error budget can withstand larger laser measurement error to achieve the same sharpening (due to trade of generalized anisoplanatism error for a more benign FA/tomography error.) Item 4 WFE budget assumptions. There is little difference as the implementation of both MCAO and MOAO models in the WFE budget / simulation tools require similar validation. Item 5 Tomography. From our perspective, MOAO reduces tomography risk by decoupling the science target tomography problem from that of sharpening TT stars. In MCAO, one's choice of LGS asterism is limited to a relatively wide asterism (typ. 40" - 60" diameter) in order to sharpen TT stars. With our MOAO Point and Shoot architecture, we can bring the science asterism in to a smaller diameter, which simulations show (KAON 429) results in lower tomography error. Item 6 Astrometry. This was one of the reasons we chose MOAO over MCAO. We were uncertain about the field stability of MCAO, while MOAO offers higher Strehls to reduce source confusion. Although MCAO reduces the initial tilt anisoplanatism error across a moderate field of view, we are ultimately most concerned about the systematic floor. We feel that the best astrometry will arise when the AO system itself is limited in it's ability to distort the science plate scale, as is the case for MCAO. Item 7 Tomography computer architecture. More DMs must be controlled in MOAO, but the scale of the problem is similar. Item 8 Keck Interferometer. With MCAO we could potentially better correct both the on-axis and the off-axis star in dual star mode, at the tradeoff of somewhat lower correction of one. With MOAO we could chose a point in the sky to optimize between these two stars (making either only 15" off-axis). For IR observations, this results in relatively little anisoplanatism. Item 9 Complexity. There are the same number of DMs and TT stages per science path, for MCAO and MOAO. The new complexity for NGAO is the multiplexed deployable IFU approach. Item 10 Wavefront sensor CCDs. The same risks apply to both MOAO and MCAO.

BLE	15	RIQ	452/5	All	All	What is the impact of the MCAO/MOAO tradeoff on the programmatic risk assessment matrix, particularly schedule risks?	PW DG CM	KAON 566 discusses the programmatic risks. None of these were identified as specifically MOAO risks, but more to do with the scale of the project and procurement risks. For the narrow field high-Strehl relay, we do not see a significant added schedule risk for MOAO as compared with MCAO, in view of the fact that we already have a 64x64 engineering grade MEMS in house for testing. However the multiplexed deployable IFU does have added schedule risks because of the multiplexing aspect. The presence of MEMS in each arm makes this schedule risk somewhat higher.
BLE	16	RIQ	452/6	All	All	What is the impact of the MCAO/MOAO tradeoff on the cost estimate, particulary if the order of wavefront correction is scaled back to 32x32 or 20x20?	RD	The costs would be reduced by ~$2100k in going to 32x32 or 20x20; this consists of ~$500k for the three LOWFS MEMs, ~$600k for reduced RTC hardware, and ~$1000k for reduced assembly, I&T and commissioning labor. On the other hand the cost to implement MCAO to replace the MOAO correction is estimated to be ~$1700k to $2600k; this includes $300k to $1200k for a 2nd DM (20x20 or 32x32), $400k for increased RTC hardware and ~$1000k for increased assembly, I&T and commissioning labor. The bottom line is no net cost savings.
BLE	17	RIQ	470	all	all	What is the quantitative impact upon sky coverage if the PnS lasers are omitted from the system? What is the impact if MOAO is replaced by MCAO?	RD PW	Our modeling predicts that MOAO and MCAO provide comparable image sharpening for the TT stars out to a radius of ~30". At this point the MOAO performance begins to fall off quickly while the MOAO PnS lasers are predicted to provide a J-band Strehl of 30% at the edge of the field versus 5% with MCAO correction. By itself this provides a factor of ~4 in available guide stars. No additional laser power is incurred for point and shoot; this is just a redistribution of laser power. A trade study is getting underway to understand the quantitative sky coverage benefit of point and shoot.
BLE	18	RIQ	471	all	all	The use of spread-sheet based error budgeting tools for an AO system of this level of complexity is an oversimplification that may (i) neglect interactions between the terms in the budget and (ii) make it difficult to study implementation errors in detail. How has the error budget tool been anchored against more detailed models, and what improvements to the budget tool are planned for the next phase?	RD CN PW	The WFE budget tool used by NGAO is a significant development of the SD phase that treats a wide variety of physical effects at what we believe are appropriate levels of detail for our major design decisions. It includes some error estimates based on first principles (e.g. DM fitting error), some estimates based on real optical measurements (e.g. telescope fitting error (KAON 469)), and some estimates based on parametric models grounded in more detailed stand-alone numerical codes (e.g. background model in KAON 501, LGS tomography in KAON 429, and Arroyo.) Key interactions between systems (e.g. sharpening of LOWFS NGS by the NGAO system to improve science tip/tilt measurement, Rayleigh backscatter degrading the HOWFS measurement) are encoded in the tool. The WFE budget tool has been anchored against both the independent Keck AO wavefront error budget developed by Marcos van Dam, and against the actual, on-sky performance of both the Keck and Palomar AO systems (in both NGS and LGS mode). The comparison with Keck is described in KAON 461. In particular, for the calculation of tomography error, three independent codes (LAOS/TAOS written by Ellerbroek, a minimum variance estimation tool written by Flicker and TSW written by Gavel (see KAON 475)) were compared to confirm that our LGS-density based approach to estimating tomography error was sound and interally consistent. Static and dynamic telescope errors were provided by studies documented in KAON 469 & 482. Sky coverage was checked against an alternate tool in KAON 470, as compared in KAON 504. The optimal LOWFS architecture was simulated in KAON 487. Most of the reports mentioned above used detailed Monte Carlo computer simulations to explore relevant parameter space. For simplicity they focused on one effect and as such are not "all in" simulation of NGAO. Parametric scaling laws (curve fits) from the results of these detailed studies are used in the spreadsheet tool. Having said this, we recognize there remains room to improve the tool. In particular, we are not happy with the method in which bandwidth error is handled and plan in the PD phase to rework our model of temporal errors to be more closely aligned with expected integration times, compute latencies, and DM latencies. We intend to re-anchor the tool to KAON 461 results after these changes.
BLE	19	RIQ	564/570	all	all	Have basic requirements for the allowable mass, volume, power, cooling, and heat dissipation been established for the lasers and their enclosure?	PW	Baseline requirements have been assigned in Tables 3 and 4 of KAON 582.

NHU	1	RIQ	575	5.1.2.1	11	As you say, specification of the spaxel is a difficult compromise between resolution, EE and surface brightness of the Galaxy: 70 mas is rather small for high-z galaxy observation on a 10 m telescope. Did you actually run simulations on typical objects you intend to observe with the IFU to make sure this is the best compromise?	CM	As you know, there are many "high-z galaxy science cases", some needing larger spaxels (e.g. Lyman alpha emission from the largest galaxies at z~ 2.5) and some requiring smaller ones (e.g. studies of the distributions of star formation rate and metallicity within galaxies at z ~ 1). We have done simulations of an OSIRIS-like IFU with the planned lower levels of background emission, and found that NGAO with its current specifications gives a large improvement in signal to noise ratio for most high-redshift science cases. The most difficult case is that of fuzzy diffuse Lyman alpha emission from the largest galaxies at z > 2.5; this case prefers 0.1 arc sec spaxels. Further optimization of the spaxel scale over several specific high-z science cases will be done during PDR phase.
NHU	2	RIQ	575	5.1.2.1	12	50% EE in 70 mas is actually an aggressive specifications which will require a high order AO system and consequently a high power LGS. Did you run simulations on actual High -z galaxies justifying this requirement?	CM	We did run simulations for this requirement (see above). We plan to refine the trade space during the Preliminary Design, to optimize the science return and to investigate the effect of lowering the laser power.
NHU	3	RIQ	575	5.1.2.1	12	The link between the Sky Coverage of 30% and the number of galaxies observable 200 is not straighforward. The number of suitable guide stars for low order correction is highly variable depending on the galactic latitude. How did you determine the number of 200 galaxies? and what is the assumed maximum guide star brightness and maximum angular distance?	CM RD	1) In large well-studied fields such as COSMOS or the Extended Groth Strip, there are more than enough tip-tilt guide stars to observe 200 galaxies with 4 galaxies per square arc min and 30% sky coverage (see pages 18 and 25 of the SCRD). We studied this in some detail for our original proposal (see page 64 of KAON 400) in order to convince ourselves that the 30% sky coverage spec was attainable. It is. 2) Since the competition for Keck observing time is high, we wanted to assure ourselves that one could observe 200 high-z galaxies within two years with a plausible time allocation. If we assume 3 hour exposures (SCRD, Figure 4, page 21) and 6 IFU arms, one can do 3 exposures per (non-cloudy) night to observe 18 galaxies per night. In that case it would take 11 nights with good weather to observe 200 galaxies. In a consortium of a few Keck observers this is a reasonable number of nights for a large program over a two year period. For the 30% sky coverage case the faintest guide star is V ~ 19 at 60" radius.
NHU	4	RIQ	575	5.1.2.1	12	What is the current performance of OSIRIS with the KAO system in term of EE in a spaxel of XX? What fraction of the above 200 galaxies are already observable with OSIRIS KAO?	DLM CM	Assuming the *best* current performance, an LGS Strehl of 0.4 in Kp band, the ensquared energy for OSIRIS within 50 mas is ~35%. However for the high-z galaxy science case, TT stars are faint (R>17) and at a separation of at least 40". This leads to an OSIRIS Strehl of 15-20% in Kp band (15 min exposure). The ensquared energy within 50 mas under such conditions is currently 10-20%. The fraction of the 200 high-z galaxies that could be observed in 3 years with the current AO system and OSIRIS is < 10% (20 galaxies) for the following reasons: 1) Sky coverage with Strehl ~ 0.2 is < 10% for these extragalactic fields 2) Total integration time is at least twice as long as NGAO because of lower Strehl and higher NIR background. Keck astronomers are currently limited to the brightest high-z targets, which only correspond to a small fraction of the 200 high-z galaxy sample. 3) OSIRIS does not offer multiplexing. Today a maximum of 2-3 (bright) high-z galaxies are observed with OSIRIS on a typical LGS night.
NHU	5	RID	575	5.1.2.2	14	The value of the tip-tilt error requirements of 15 mas rms looks somewhat large for the narrow field imager? The excellent AO corrected PSF will probably be blurred due to tip-tilt?	CM RD PW	For the narrow-field imager the inherent tip-tilt error requirement for a bright close-in tip-tilt star is much lower than 15 mas. For example the requirement is 3 mas rms for the Galactic Center. The requirement of 15 mas that you quoted is the requirement on maximum tip-tilt error that would result from 30% sky coverage, and this is readily met given the statistical distribution of infrared tip-tilt stars on the sky.
NHU	6	RIQ	575	6.2	17	The LGSs are launched from behind the secondary. Did you analyse the rayleigh scattered light in the visible science FoV? Did you evaluate the Rayleigh Fratricide effect?	PW VV	KAON 490 reports on an initial Rayleigh rejection trade study. The fratricide discussion drew on Ellerbroek and Gavel's simulations for Gemini MCAO; a factor of two reduction in SNR is expected for the worst affected subapertures. We have a fratricide simulation code (developed for Gemini MCAO and modified for the original NGAO variable quincunx asterism geometry) available which we will use for detailed simulations of the different asterism geometries during the preliminary design. The equivalent sky brightness due to Rayleigh backscatter based on a Subaru/Keck experiment is also discussed, however we do not plan to perform science at wavelengths as short as 589 nm.

NHU	7	RIC	455		14	Note that GALACSI at the VLT has also a so-called narrow FoV mode (LTAO) which aims at providing 5-10% Sr (650 nm)	PW	Thanks for this additional information. We will add it to our comparison table (table 1 in KAON 455).
NHU	8	RIQ	455	2.2.4	31	I did not find the quantitiative evaluation of the PSF stability improvement brought by the NGAO and the corresponding analysis leading to the science conclusions in this section. What is the PSF knowledge accuracy expected by this science case?	CM PW	The graphs shown in the "Nearby AGN" science case (KAON 455 sections 2.2 3 and 2.2.4) were made simply by using a Gaussian fit to the core of the PSFs simulated by Neyman and Flicker (KAON 466 and http://www.oir.caltech.edu/twiki_oir/bin/view/Keck/NGAO/PSFlib). They do not yet take into account PSF stability considerations. This is one of our tasks for the Preliminary Design Phase. As we have already been able to see the Keplerian velocity turnover (shown in Figure 7 of the SCRD for a galaxy at 20 Mpc) for a galaxy at 100 Mpc, we are generally encouraged that Figure 7 is not unrealistic. We have not yet quantified the PSF stability and knowledge requirements, from the perspective of the overall astrometric and photometric requirements. Quantifying these requirements is a major systems engineering task scheduled for the Preliminary Design.
NHU	9	RIQ	455		37	I am not sure to understand how the NGAO will be able to provide 150 microarcsec astrometry accuracy for this science case? NGAO is not an MCAO system (?) therefore the PSF will not be more uniform or did I miss somehting?	PW CM	The UCLA Galactic Center group have already demonstrated position uncertainties at the ~ 150 micro-arcsec level on the brighter sources (10-15 mag) with the current Keck LGS AO system as shown in KAON 480 and in their most recent Keck results. In regions of very high stellar density such as the Galactic Center, measurements of stellar position are biased by the unresolved stellar background. Preliminary simulations show that the improved Strehls provided by NGAO will significantly reduce the source confusion thereby leading to higher astrometric accuracy. In the Galactic Center the astrometry solution is done on approximately 1000 stars simultaneously, thus providing redundant information and increased accuracy.
NHU	10	RID	455	2.4.5	48	The WFE specified for NGAO seems to be 170 nm rms. It is therefore important to evaluate wether the required contrast for this science case can still be achieved. I am wondering whether the current cophasing error of Keck primary mirror is actually compatible with contrast required by this science case? How much NGAO will be able to reduce this error?	PW CM	NGAO's high contrast and companion sensitivity performance was evaluated in KAON 497 versus the planets around low mass star science requirements (Table 4 in KAON 455). This analysis did include the contributions from Keck telescope errors. The bottom line is that the companion sensitivity "requirements" for target Sample 1 and 2 are expected to be met. The "goal" for target Sample 2 and the tougher of the two "goals" for Sample 3 cannot be met currently. The looser Sample 3 "goal" may be possible to achieve. Sample 1 is old field brown dwarfs to 20 pc; Sample 2 is young field brown dwarfs and low mass stars to 80 pc; Sample 3 is solar type stars in Taurus and Ophiuchus, and young clusters at 100-150 pc.
NHU	11	RIQ	455	2.4.6.2	49	I guess the overhead per target (5 min) is quite challenging for a multi LGS system?	PW CM	The top-level science requirement is on observing efficiency. For the planets around low mass stars case that you reference the efficiency requirement is to obtain the required science data on 20 targets per night (KAON 455 Table 4). We have started putting together observing efficiency budgets such as the one shown for the high-z galaxies science case in the observing efficiency section (section 3.6.1.2, figure 53) of the System Design Manual (KAON 511). The acquisition time used in this observing efficiency estimate are from experience with the Keck AO system and our knowledge of the NGAO design. Yes, five minutes may be too challenging, but we are looking at the overall efficiency budget to determine how the science requirements can be met. Note that Mike Liu's Keck II LGS AO Brown Dwarf survey has 7-9 minute overheads between targets.
NHU	12							
NHU	13	RID	504		1	The expected performance of 50% in J band looks quite optimistic even with a 32x32 actuator DM? Did you actually simulate this using the LTAO or the one LGS on the LOWFS NGS? Any problem with the cone effect for instance?	RD	For the KBO science case (10% sky coverage), we typically use relatively close-in tip/tilt stars which enjoy rather good correction (due to rather low ~50nm tomography errors). The remaining allocable ~159 nm WFE has at it's largest term atmospheric fitting error (due to 32 x 32 MOAO correction in the LOWFS). For the Extended Groth Strip case, we do not typically see J-Strehls on the NGS of 50%, but rather closer to 35%. In our NGS sharpening model, the tomography term in the error budget transitions smoothly from the on-axis tomography error from the science asterism to the focal anisoplanatism error obtained for single-LGS (using a Cn2 optimal reconstructor). For the EGS science case of KAON 504, the EGS science case tomography error is 119 nm. This term of the tip/tilt star error budget results in J-Strehl = 0.70 alone. To typically see 35% J-Strehl on Point-and-Shoot stars, the total otherwise allocatable WFE for the NGS is ~162nm, similar to non-tomography errors allocated in the KBO science case.
NHU	14	RID	504		2	The atmosphere conditions and the sodium abundance assumptions looks optimistics. The percentiles assumed here should in principle be compatible with the expected exposure time on the science object. For high redshift galaxies science, this can be as long as several hours. Therefore, percentiles of seeing, Tauo etc... should be closer to 25%. NGAO, should also be able to observe under low sodium abundance down to 1 10^9? What is the assumed number of sodium photons/W in thsi simulation?	RD	We assumed median seeing (r0 = 16 cm) and median sodium abundance (4x10^9 cm^-2) to the extend the later is inferred for Mauna Kea, during the SD phase. We interpret this to mean that 50% of the time NGAO will exceed the performance estimate and 50% of the time fall short. We have not considered seasonal correlations of seeing, tau0, sodium abundance, etc. in the SD phase to estimate, for example, monthly performance estimates throughout an observing year.

NHU	15	RIQ	504		2	M type star are really red. Is that a realistic assumption to compute the sky coverage?	RD	The majority of stars useful for our LOWFS are very red. For the brighter stars mV < 16, M- and K-type stars make up 88% (see http://adsabs.harvard.edu/abs/2001JRASC..95...32L); we assumed all stars were M0 in the sky coverage calculation. In the range of mV = 18-20, we do not know the exact distribution, but the bias toward low-mass, redder stars is clear. Our sky coverage calculation tools allow us to easily consider tip/tilt measurement error using one, two, or three field stars of user-definable (but uniform) spectral type. To illustrate the dependence on color, we reconsidered the Galaxy/Galaxy Lensing Science Case, which requires 30% sky coverage at b=30. Assuming M-type TT stars, we find we would typically choose mV = 18.1 NGS (mH = 14.3) that are 49.2" from the science target, at 500 fps, for 'bottom-line' performance of 224 nm rms. Changing our stellar type to G, we would typically choose mV = 16.2 NGS (mH = 14.7) that are 54.1" from the science target, at 475 fps, for 'bottom-line' performance of 226 nm. For this science case, there is relatively little dependence on our color assumption. (In practice, as we change type, we shift the distribution of light in the LOWFS from H-band (higher Strehl, but broader PSF) toward J-band (lower Strehl, but sharper PSF.)
NHU	16	RID	504		2	Is the RON of 4.5 e at 700fps a realistic value for the H2RG detector?	RD GR	Noise measurements made on a H2RG at Caltech show that a read noise of 3.5 e- can be obtained when reading out 12 pixels using Fowler 8 sampling at an equivalent ROI rate of 490 fps. Our extrapolation to 4.5 e- at 700 Hz needs to be confirmed. These relatively new results (generated in support of PALM-3000 IR TT sensor development) will be incorporated in more detail (e.g. noise vs. frame rate) into our error budget in the PD phase. (As an aside, these data will also inform the current CIT/HIA LOWFS study for TMT IRIS.)
NHU	17	RIQ	504		4	What is the rms tip-tilt error associated to the curve of Figure 2	RD	For the case described in KAON 504, Fig. 2, high-order errors result in an H-band Strehl ratio of ~0.67 while the 1-D tip/tilt error is ~11.9 mas for b = 30. At b = 90, the 1-D tip/tilt error has increased to ~13.7 mas. Adding this to the diffraction limit in quadrature results in a FWHM ~ 34 mas.
NHU	18	RID	504		4	What is the expected acquisition time of a low order NGS of magnitude 21? Is this overhead acceptable by the science?	DLM	Tables 3 and 4 in "NGS and LGS Acquisition Subsystems for NGAO: Initial Requirements and Conceptual Design" (KAON 567) provide estimates for the acquisition overhead for fainter stars (up to V=22). The acquisition camera should be able to detect a V=22 star in 10 sec with SNR~10 (Table 3). The steps for NGS acquisition and centering on the LOWFS/TWFS should take ~2 min (table 4). The main risk for the science overhead is the duty cycle on the LOWFS and TWFS, that could lead to lower bandwidth (~1-0.05 Hz) on the low-order and offset centroid loops every time the AO loops are open/closed. Yet, this problem is mostly overcome if we implement a dither method that does not require the loops to open (as recommended in KAON 558). Section 3.6.1.2, figure 53 of the System Design Manual (KAON 511) provides an estimate for the observing efficiency for the high-z galaxy science case with faint NGS. It estimates the overhead for the NGAO acquisition time to be up to 12 min including telescope slew, and shows that we can reach 80% observing efficiency. We believe that the acquisition of NGS of J~19, V ~21 will not prevent us from reaching our science goals.
NHU	19	RIQ	549		23	Figure 5: I guess the field steering mirrors are used to acquire the NGS and to compensate for differential refraction between the NGS TT and the instrument? Do you need to refocus one of the two mirror to compensate for differential optical path in the FoV?	PW	Yes, the field steering mirrors (FSMs) allow you to acquire the NGS while maintaining the lenslet-to-DM registration. Similar FSMs are used in the existing Keck AO systems. In the current system differential atmospheric refraction (DAR) is compensated for by changing the centroid offset during a science integration. Whenever an opportunity arises (the field is dithered, a science filter is changed, etc.) the DAR offsets are then applied to the FSMs. For NGAO we will likely make the FSMs tracking devices so that the DAR offsets can be directly applied to the FSMs. This would also allow for differential tracking. Focus corrections versus field position are applied to the focus stage on which the wavefront sensor is mounted.
NHU	20	RIQ	511	3.3.1.1	10	The low order DM is mounted in a tip-tilt mount. What are the temporal characteristics of this TT mount and the expected rejection of the telescope and atmospheric tip-tilt?	PW RD	We do not know the temporal characteristics of this mount yet. The dyamics of the the TT mount for this DM have been identified as a risk item (item 12 in KAON 510) that we plan to address during the preliminary design. We have the option of a woofer-tweeter arrangement either using the tweeter TT mounts or the DM to obtain higher bandwidth. The -3db tip-tilt rejection that we are assuming in the error budget (KAON 471) is 20 Hz on relatively faint tip-tilt stars. This increases to 39 Hz on bright tip-tilt
NHU	21	RIQ	511		15	Pupil distorsion of 1.5% looks large (~ one subaperture if I am right)? What is the effect on this mismatch on the AO correction? How do you calibrate this distortion into account in open loop?		Yes, this does represent a total of 1 subaperture when moving from one edge of lenslet 1 to lenslet 64 (or 0.5 subapertures when moving from center to edge). The mapping of the LGS WFS measured errors along this axis will need to be appropriately magnified before application to the MEMS DM. The calibration issues will need to be carefully thought through in the next design phase. One potential approach would be to register the NGS WFS lenslets to the MEMS DM and then make the same measurements with the on-axis LGS WFS and NGS WFS, using a simulator source, to calibrate the LGS WFS lenslet registration and scaling to the MEMS DM. The narrow field TWFS will provide a semi-real-time calibration capability.
NHU	22	RIQ	511		18	What is the assumed on-sky laser spot size leading the the LGS WFS pixel scale of 1.45"?	PW	Table 2 of KAON 551 shows the calculation of LGS spot size. This is 1.7" on average and 1.9" for the maximum elongation, including wavefront sensor effects.
NHU	23	RID	511		18	The Bandpass of the TT & TTFA does not cover the full J or full H band. This does not look consistent with the Sky coverage computed in the note 504?	PW	Thanks for catching this error in the System Design Manual. The actual sensing wavelength is 1000-1800 nm as shown in Table 1 of KAON 551.
NHU	23	RID	511		19	Same remark as above the TT and TTFA detectors seems to have a larger RON here than in note 504 (7 & 4.5 e)	RD PW	The requirement is 7e- but the performance predictions have tended to use 4.5 e- (which seems achievable; see the response to NHU 16). We compared the impact of 4.5 vs 7e- on sky coverage and found that this is not a big impact for the Galaxy Galaxy lensing (30% sky, narrow field science) case.
NHU	24	RID	511		18	Pixel scale of 1.5" for the NGS WFS seems pretty large and will be undersampled for good seeing?	DG RD	The optimum choice of Hartmann spot size in pixels on the detector trades against the choice of centroiding algorithm. The studies in [1], [2] give a general guidance that pixel scale slightly larger than the spot full-width-half-max gives best performance trade of signal to noise and linearity. This has been confirmed in our experience with accurate wavefront sensing using the Villages Hartmann sensor on sky with a 2 arcsecond WFS plate scale. For NGAO NGS HOWFS, we have tentatively selected 1.5" per pixel based on our model of centroid size that includes seeing, diffraction, field stop transmission, charge diffusion estimates and other factors (including our desire for NGS science on Galilean satellites without change of plate scale.) We find that the wavefront error budget prediction is rather insensitive to small perturbations about this value, but we do expect our final choice of plate scale to evolve during the PD phase. [1] S. Thomas, T. Fusco, A. Tokovinin, M. Nicolle, V. Michau, G. Rousset, "Comparison of centroid computation algorithms in a Shack–Hartmann sensor," Monthly Notices of the Royal Astronomical Society, Volume 371, Issue 1, Page 323-336, Sep 2006. http://www.blackwell-synergy.com/doi/pdf/10.1111/j.1365-2966.2006.10661.x [2] Thomas, Adkins, Gavel, Fusco, and Michau, "Study of optimal wavefront

NHU	25	RIQ	511		19	What is the detector you are planning to use for the HOWFS (256x256 with RON of 3 @ 2 kHz)?	SA	It will be based on the 160 x 160 pixel CCD developed through AODP funding in collaboration with MIT/LL (~1e- RON at 1MHz pixel rate). For the NGAO LGS WFSs (HOWFS) a larger device (256 x 256) is required, and achieving a 2KHz frame rate with the larger device would require ~3.5MHz pixel clock rates. This will require a 2 stage amplifier, such as that implemented on a recent variant of the CCID-56, called the CCID-66 which uses a planar JFET as the first stage, and a conventional MOSFET as the second stage to support higher pixel clock rates at the expense of an increase in read noise. Test data from these devices is not yet available, but based on appropriate mathematical extrapolation from the performance of the CCID-56 the figure of 3e- at a 2HKz frame rate appears sufficiently conservative.
NHU	26	RIQ	511		19	I am not aware of a IR detector of 7 e RON at 500 Hz full frame?	VV	Please see the response to RQF's question #16.
NHU	27	RIQ	511		20	What is the expected accuracy of the LOWFS OSM? Is this accuracy compatible with the requirement to correct for differential atmospheric refraction? This means that the tracking window on the IR detector will have to be moved in real tim eas well. Is this a problem?	PW	The probe arm requirements flow directly from the science image positioning accuracy and knowledge requirements and are summarized in Table 2 of KAON 562: acquisition accuracy = 40 mas (30 um), stability = 1.4 mas and positioning knowledge = 1 um. These requirements should be met by off-the-shelf rotary mechanisms. Differential atmospheric refraction (DAR) compensation when using the LOWFS could be addressed in a number of ways: 1) For small DAR corrections centroid offsetting could be used. 2) For slightly larger DAR corrections the tracking window could move as you suggest. 3) Somewhat larger DAR corrections could be provided by the MEMS/TT stage in the LOWFS unit. 4) The largest corrections could be provided by moving or tracking the probe arm. 5) Alternatively for d-IFS science options 3 or 4 could be performed with the d-IFS MEMS/probe arms. 6) Alternatively for narrow field LGS science the narrow field MEMS TT stage could be used for DAR compensation while the LOWFS remain fixed. We plan to determine our preferred approach or combination of approaches during the preliminary design.
NHU	28	RIQ	511		22	What is the expected end to end transmission from Nasmyth to NGS TT IR detector focal plane? Is this compatible with the limiting magnitude expected?	VV PW RD	The end-to-end transmission is 0.16 for the TT sensors and 0.09 for the TTFA. The transmission model assumes realistic reflectivities/transmissions for mirrors, MEMS, dichroics and windows, and lenslet scatter. The limiting magnitude takes into account these transmissions.
NHU	29	RIQ	511		24	I am not sure to understand why the MEMs is mounted on a TT mount in figure 16?	PW	It may be that this is not required if the TT stage in the wide field relay can achieve the required performance for narrow field science. For the moment we have included this TT mount to ensure that the required narrow field TT performance can be achieved. It may have other beneficial roles to play as well such as DAR compensation (as mentioned in response to your item 27).
NHU	30	RID	511	3.3.2.6	27	Is it not better to compensate for the LGS jitter at the LGS WFS input beam instead of doing this at the level of the launch telescope?	PW	Yes, we believe that it is. Apologies for not having explained this in the design manual but our current intention is to perform the LGS jitter correction in the LGS WFS feed. The option of LGS jitter compensation in the laser projection has also been included in the current design, but will be removed as we further develop the jitter compensation design.
NHU	31	RIQ	511	3.3.3.1	31	Are you sure that the LGS spot size will be 0.5"?? Or do I misunderstand here?	PW	This unfortunately represents the state of our optical design for the feed to the LGS WFS. The LGS optical performance is inadequate and we plan to develop a better design during the preliminary design. There is no fundamental reason that an acceptable design cannot be developed (for example, an Alverez style corrector plate was suggested or a 2nd OAP can be used).
NHU	32	RIQ	511	3.3.4	37	Is there any problem to cool down MEMs at -20C?	CM PW	MEMS in general have an excellent record of operating at cold temperatures. Although we have not yet tested our Boston Micromachines mirror at -20C, Boston has designed a very similar DM for NASA to fly on the (now-cancelled) Terrestrial Planetfinder mission at temperatures much colder than this. We plan to test the Boston MEMS at the desired operating temperature.
NHU	33	RIQ	511			What is your plan to calibrate the MEMs control in open loop?	DG	We have successfully calibrated a BMC 144 actuator MEMS in the LAO using the method described in [1]. The open-loop performance of this same mirror has been confirmed on-sky in the Villages experiment. A similar approach will be taken with the 32x32 and 64x64 MEMS. [1] Katie M. Morzinski, Donald T. Gavel, Andrew P. Norton, Daren R. Dillon, Marco R. Reinig, " Characterizing MEMS deformable mirrors for open-loop operation: High-resolution measurements of thin-plate behavior," SPIE Photonics West, Vol. 6888, January, 2008. http://lao.ucolick.org/twiki/pub/LAOLibrary/LibraryEntry95/Morzinski_OpenLoopThinPlate_spie688827.pdf
NHU	34	RID	511		47	The availability of the 50W sodium laser is one of the critical item for the NGAO project (and also for some other important AO projects in the world). What is the planned strategy between now and the PDR to reduce to an acceptable level this risk.	PW	We very much agree about the criticality of this issue. This risk item and our plan to address it are discussed in KAON 566 (item 2 in the table and sections 4.1 and 4.2).
NHU	35	RID	511		49	The sodium return flux assumption is sufficiently critical to be addressed at the review meeting carefully. Impact on the AO performance might also be discussed.	RD DG	We will discuss performance vs. photoreturn during the review. The error budget spreadsheet allows us to assess the impacts of sodium density, choice of laser format, etc. The spreadsheet models are tied to recent LGS on-sky results and sodium response models which are summarized on the web page http://lao.ucolick.org/twiki/bin/view/CfAO/SodiumLaserGuidestars

NHU	36	RIQ	511		61	The number of degrees of freedom to be controlled (190) in the NGAO system is 5 times larger than in the current AO system. From the experience with the current AO system, can you estimate the MTBF of the NGAO?	PW CN	The motion control electronics have been very reliable in the existing Keck AO systems. We have had problems with some stages (which could be reduced with better preventative maintenance). Failures during a night have been rare, with the exception of one poorly encoded stage in the laser pointing control. One of the identified goals for the preliminary design (KAON 569, section 7) is to simplify the motion control design and only use the minimum number of controlled devices required. We have identified complexity failure as a technical risk area requiring attention in KAON 510 (item 9). As a demonstration of feasibility of low downtime for a complex system the Keck interferometer has ~ 120 motion control devices (excluding ~ 90 two position devices). This is operated with the two AO systems with overall lost time in the range of 5-10%. The existing Keck II LGS AO system has 40 motion control devices for the AO bench and another ~20 devices for the laser. Servo control is provided by 5 PMAC boards for the bench and another 3 for the laser. The increased motion control scale with NGAO is 190/60, a factor of ~3.
NHU	37	RID	511		61	The large amount of degrees of freedoms to be controlled (motions and multi DM, TT, Sensors, RTC etc…) will require large electronic cabinets and cabling. How this taken into account the present NGAO concept; do you have space, power & cooling power provisions for these cabinets? Our experience with the BMM MEMs is that cabling is an issue especially if one intends to mount these DMs on tip-tilt mount. what is your approach to improve that aspect.	PW EJ DG	Initial discussions indicate that we will be able to address the space, power and cooling requirements. The existing Keck AO systems have all of the 40 channel motion control in a single 19" rack with some room to spare. We plan to look at cabling issues for the motion control system in a trade study to be conducted during the PD phase. The trade study will address the overall motion control architecture, specifically looking at the pros and cons of a centralized system vs a distributed system, and taking into consideration the impacts on electonics placement, cooling, and cabling. We will also address the MEMS cabling issue during the PD. Electronics space and cabling requirements have been roughly scoped out in the FRD. We believe adequate space, power, and cooling exists in the infrastructure available on the Nasmyth platform. MEMS cables are a high-tech issue now presently being addressed in the Gemini Planet Imager project. GPI will use a 64x64 MEMS mounted on a tip/tilt stage. The stage and cabling have already been designed. Manufacturing the cables is tough, but we expect our first set for testing the engineering grade MEMS within a month.
NHU	38	RID	511		71	NGAO is clearly a cahllenging system from the point of view of Real Time Computer. The number of LGS WFSs, DMs and actuators expected to be driven in Multi tomography mode at 2kHz is extremely large. The number of operations required by NGAO is therefore beyond what is planned to be built now (even for TMT). The proposed approach making a massive use of FPGA (if I understand correctly) is theoritically appealling. However, I am concerned by the fact that FPGA does not offer large flexibility during optimisation of the AO system. Since the type of AO systems implemented by NGAO is rather new (MOAO, LTAO, etc…), my impression is that the NGAO team will have great difficulties to optimise the system or will take a large amount of time and FTEs. Futhermore, since all these types of AO systems are not yet fully mature, new ideas or new ways to control these systems will significantly evolved in the coming years and these new ideas should be taken into account for NGAO.	DG	Yes it is a challenging and interesting problem. The MPP design approach we have taken has been based on breaking down the problem into its basic key algorithms and allowing for a maximum of flexibility in combining the building blocks. The design will allow either of the presently proven stable LTAO algorithms: Fourier-Domain Pre-conditioned Conjugate Gradient Back Projection Tomography, and V-cycle Multi-grid Spatial Domain. The design will also allow full flexibility in number of modeled atmospheric layers, number of subapertures in wavefront sensors, number of DMs, DM architecture (MOAO or MCAO), a-priori Cn2 model, asynchronous WFS frame rates, etc. The needed compute power scales with "problem size" (e.g. number of layers or number of subapertures) but the MPP architecture can track this with additional identical FPGA-populated boards and maintain overall system throughput rate.

NHU	39	RIQ	511		79	The open shutter of 80 & 70% looks ambitious taking into account the current open shutter time obtained at most of the LGS observatories. Are you planning to invest some effort during the PDR phase to bring the Keck LGS system to that level as well?	DLM	Section 3.6.1.2 of the System Design Manual (KAON 511) and KAON 463 on “Lessons learned from current operations” provide an analysis and discussion on the statistics for open shutter time. Most of the losses are due to our limited abilities to handle parallel commands to subsystems and will not be easy to retro-fit due to the architecture of our current LGS system. The statistics on the science with OSIRIS (where long exposure of 15 min are the norm) has shown that we can reach 80% observing efficiency. There are still additional factors that we are planning to optimize for K2LGS and K1 LGSAO: better accuracy for blind centering, better planning and handling of closures from the Laser Clearinghouse, better duty cycle and increased bandwidth using a 5x5 lenslet array for the LBWFS.
NHU	40	RIQ			79	I agree that weather should not be included in the evaluation of the open shutter time unless the weather impact is affecting mostly the operation of the LGS mode (cirrus for instance?). Do you agree?	DLM	The definition of weather losses depend on the observing/science operation model. There are different factors that may impact the performance (and stability) of the LGS system: poor seeing, wind, Na return and transparency. All these factors are atmospheric factors. If transparency is null (extinction > several magnitudes at wavelength of interest), then it is admitted to be a weather loss. For LGS operations at Keck, we consider a *weather loss* when the extinction on the LGS spot (and particularly the laser scattered light on the cloud) precludes the LGS operations (extinction ~ 1-1.5 mag). We agree that at the end what matters is to keep track of the statistics of the weather loss and see its impact on the science planned for an observing semester. From KAON 463, we anticipate that NGAO will be able to function in LGS mode in ~65-70% of the time, and in NGAO mode ~75-80% of the time.
AMG	1	RIC				This looks like an exciting and important program for Keck!	CM	Thanks! We agree!
AMG	2	RIQ				With HST/WFC3 and JWST, why isn't the complementary sweet spot near diffraction-limited work? In the SCRD, the science case makes a plug for resolution of 70 mas, but in the SRD this appears to be degraded with a spaxel size become limited to 70 mas (p. 11). Degrading the resolution will take away from the uniqueness of the work that can be done by Keck. This may just be an inconsitency in the document, as Appendix B is back to 35 mas (Extragalactic science case)	CM	As a clarification: The "narrow field" AO relay *is* for diffraction limited work. That's where we are aiming for high-order Strehl ratios of 80% or more in K band. The deployable IFU instrument, d-IFS, is where we specify a spaxel size of 70 mas. This is a compromise between many different specific science cases, and is not optimum for all. For example: 1) For galaxies at 2 < z < 3 an important area of study is emission-line imaging in Hα or [OII] or [OIII]. Hα emission is frequently extended at this z. Results from OSIRIS indicate an optimum spaxel scale of 0.1 arc sec or even larger. 2) For galaxies at 0.5 < z < 1.5 NGAO will have enough native spatial resolution to study the spatial distribution of velocities, metallicity, and star formation rate. With NGAO's lower backgrounds the optimum spaxel size is 35-50 mas. 3) For radial velocities of individual stars in the Galactic Center the optimum spaxel size is 20 - 35 mas or perhaps even smaller. So the science cases include a large range of preferred scales. The choice of d-IFS spaxel scale will be analyzed in more detail in the PDR phase.
AMG	3	RIQ				Another graduatl shift from the Science case, tto he requirements in the SCRD, to the SRD is the argument about the FOV of the IFU units for sky subtraction. Initially it is stated that a 1x3" assumes that a separate IFU is used for sky, but then the arguement shifts to this is the FOV necessary for sky subtraction. I suspect that this is too small for high quality sky subtraction (Extragalactic science case)	CM	Typical sizes of high-z galaxies are ~ 1 arc sec. The choice of a 1" x 3" IFU field would use the remaining 2" in the long direction to determine a sky simultaneously with the spectrum of the object. For galaxies larger than 1" to 2", one might choose to move a second IFU unit as close as possible to that for the galaxy, and to dedicate this second unit to determining the sky in a neighboring area. If it turns out to be possible, IFU fields larger than 1" x 3" would be desirable. This will be a cost-benefit trade in the design of the d-IFS.
AMG	4	RIC				MCAO impact on astrometry is a concern, because the tip-tilt stars will generally be moving themselves. This most likely introduces significant chanllenges to the problem of maintaining a stable astrometric grid. With the existing LGS-AO system, a relative reference frame in a crowded field has been shown to be maintainable to 0.15 mas over 1.5 years (5 measurements)	CM RD PW	There are concerns about astrometry with MCAO (which the TMT NFIRAOS team plan to address by pinning the field at the tip-tilt stars), which we won't face with our planned MOAO system. In general we expect that MOAO systematic astrometry errors will be low over our high-Strehl narrow field of view, but this needs to be analyzed. We will be developing an astrometry error budget during the preliminary design.
AMG	5	RIQ				What not include L' for the imager? This is a powerful filter fo embedded stellar populations and studies of circumstellar disks (both popular AO targets). The corections are better at longer wavelengths and a cooled system should show tremendous improvements at these longer wavelengths	CM	We decided not to do L' band imaging because JWST will do it so much better (more sensitively) than NGAO can, due to much lower backgrounds. However NGAO's spatial resolution at L' band would of course be better than JWST's. We will consider whether it makes sense to keep the L' band as a *goal* while doing further AO and instrument design. Our current design does not preclude L' band.

AMG	6	RIC				Larger FOV for imager is desirable. Glad to see that there was a push to increase from 10" to 30" diameter. Is this the place to stop? Power of HST/WFC3 (123"x123") is striking for many program (e.g., stellar clusters in general)	CM	The useable field of view is determined by the isoplanatic angle. The model for the Mauna Kea atmosphere that we are using has a median isoplanatic angle on the order of 2-3 sec at a wavelength of 0.5 micron, which translates to 7-10 arc sec at H band and 12-18 arc sec at K band. Thus our nominal imager field, 30 arc sec, corresponds to a field radius of one isoplanatic angle at K band. On an exceptionally good night with larger isoplanatic angle, the useable field might be as large as 40 arc sec at K band, but beyond that point it does not make sense to further enlarge the field.
AMG	7	RIC				GC is not the only program that would like a 3 mas tt error (SRD). There are lots of precision astrometry programs this system could do (see for example all the kinds of astrometry programs initiated by ACS …. IMBH in globular clusters, HVS in the halo, binary).	CM	We agree that there are many interesting and important precision astrometry programs beyond Galactic Center science. We have begun to describe them in Section 3.3 of the SCRD (KAON 455), and in PDR phase we plan to finalize the science requirements for these astrometry science cases.
AMG	8	RIQ				Why is general astrometric requirement only 5 mas? LGS-AO today easily achieves 0.5 mas relative astrometry (in non GC fields)? Clarification: The 5 mas requirement was found in the SCRD, section 5.2.2 (per Andrea)	CM	The number quoted in the SDR section 5.2.2 (page 14) is incorrect. The astrometry requirement as developed to date depends on the science case being considered. As listed in the "Rainbow Chart" (KAON 548), the requirement is 1.5 mas for asteroid companion orbit determination, 1.5-2 mas for planets around low-mass stars, and 0.1 mas for the Galactic Center. Further science cases to be considered in PDR phase (see above cell) will produce their own requirements.
AMG	9	RIC				I'm confused about the statement in the SRC that the PSF requirements will be developed in the PD phase. If unknown, how do you know what to design toward?	CM	In the System Design phase that you are reviewing, we stated the science requirements in terms of photometric and astrometric accuracy. During PDR phase we plan to translate these into requirements on the precision of our PSF knowledge with NGAO. For different science applications there are different merit functions for "PSF knowledge" - these will be defined in detail in PD phase. For example we will determine the required precision of PSF knowledge needed to study quasar host galaxies, since PSF subtraction of the central point source is needed. Separate CfAO projects under David Le Mignant & Ralf Flicker, and Matthew Britton are developing and testing methods of deriving PSFs from atmospheric measurements coupled with telemetry from the laser tomography system. As a general statement, we have listed adequacy of PSF knowledge as our number one technical risk factor, since this is a field that is not yet thoroughly understood.
AMG	10	RIC				Are there astrometric implications of the open-loop approach?	RD	NGAO utilizes the open-loop approach in two different ways. In the science path, the MEMS DM is in a pupil-conjugated location, so any open-loop control errors that arise there are applied in the same way to all points in the science field of view. Thus open-loop error cannot introduce optical distortions in the science field. (In fact, because the wide-field relay mirror is also-pupil conjugated, it should be impossible for NGAO DM's to systematically alter the plate scale.) In the LOWFS, because there are 3 separate MEMS DM's, it would be possible for open-loop control errors to apply a differential tilt among the LOWFS. However, the LOWFS controller will either interpret this as some high-altitude focus error, or will ignore it altogether (depending on control law implementation). In either case, the worst outcome could be some amount of inappropriate focus term control is applied to the science path at a pupil plane, once again leading to no optical distortion of the science field.
AMG	11	RID				SRD strehl raios in Table on p. 2 not entirely consistent with Figure . Clarification: In the SDR, Fig. 3 on p.6 and Table on p. 25 don't seem to agree.	CM	Figure 3 in the SDR shows generic performance for the NGAO narrow-field AO system. The turquoise area has high-order wavefront errors between 140 nm and 180 nm. The Table on page 25 of the SDR comes from specific (and detailed) error-budget calculations for 6 individual science cases. As can be seen in the Table, for these cases the high-order wavefront error has a larger range: from 104 nm (Io, which is its own bright natural guide star and hence produces high Strehl) to 204 nm (high-z galaxies, where the laser guide stars are spread out over 51 arc sec in order to achieve a wide field of view for the deployable IFU).

APPENDIX B

Questions regarding Keck NGAO System Design Review

By Glen Herriot, NRC-HIA, April 21st, 2008

1. How will you verify and calibrate the registration of the 7, very high-order open-loop, MEMS with the pupil?
2. How will you calibrate the non-common path errors between the d-IFUs and the LGS WFSs?
3. You mention a variety of calibration equipment. It seems to me that there is very little space for such items between the entrance window and the K mirror.
4. How do you reconcile the 3 mas T/T performance at the Galactic Centre with the 0.12 mas precision and SNR of 10, needed to observe General Relativistic prograde precession?
5. Is the window wedged? Are you concerned about ghosts?
6. What about turbulence and heat leakage at the window? Have you considered double paned and evacuated windows in the optical design?
7. The schedule has 4 years for design but only 2 years for construction until NGAO is shipped. The proportions seem out of line, and particularly tight for AIV prior to shipment.
8. I am skeptical that 1 μm positioning of probes using off the shelf components is practical at –20C. How will you calibrate pointing models when cold?
9. How will you prevent collisions of guide probes when initializing after a power failure? For Altair theta-phi stages we incorporated a sin/cos potentiometer in each stage as an absolute encoder. The fine positioning relied on incremental encoders, but the absolute encoder was used to estimate startup geometry, and as an independent safety system. Analog circuits evaluated the trigonometry and monitored for impending collisions. Finally, as a validity check, |sin^2+cos^2 - 1|<epsilon was evaluated for each sin/cos pot – otherwise it shut down the motors.
10. What do you mean by “use the TT stars to resolve ambiguities in the tomography,” since they will not be used to stretch the field?
11. What will be the acquisition camera integration time to find the stars for the LOWFS?
12. What is the path length change of telescoping LGS beam feed tube to top end vs. zenith angle? The feasibility depends on stroke, and this was not answered.
13. Circular polarization gain at MK will not be as high as at the higher latitude SOR. Isn’t there some cherry picking. RTC uses 6 LGS, but Rich argues that PnS does not waste photons since they also sample a large part of the turbulence, even at edge of field. Which is it, 6 or 9 LGS WFS feeding tomography?