Keck Adaptive Optics Note 779

W.M. Keck Observatory NGAO Preliminary Design Review

Review Committee Report

June 23rd, 2010

Elizabeth Barton, Corinne Boyer, Jay Elias, Brent Ellerbroek (Chair), Andrea Ghez, Norbert Hubin, and Matt Johns

Executive Summary:

The review committee is pleased to congratulate the WMKO NGAO team on their successful PDR. The enthusiasm, expertise, and level of work performed by the team are very clear from the presentations and the documentation provided. NGAO will represent a dramatic improvement in WMKO scientific capabilities, which will continue unmatched for many years, and which will remain competitive into the era of extremely large telescopes, JWST and ALMA. The development of NGAO is critical to WMKO's future as a facility producing forefront science and as a leader in adaptive optics development.

NGAO is necessarily a very innovative and sophisticated system in order to enable these results. The team possesses the necessary engineering and AO experience to develop such a complex system, but considerable further effort will be needed to complete and implement the design in an efficient, optimized, and cost effective way. There are some areas of the project that the committee feels are not yet fully at the PDR level:

- Possibly because the definition of PDR varies from institution to institution
- Possibly because we haven’t read 100% of the documentation!

The committee’s detailed concerns follow in the main body of the report, but our general recommendations for the future phases of the project are as follows:

- There is a need for staff to be assigned full-time to critical tasks, including project management, systems engineering, and operations planning. Currently empty positions should be filled as quickly as possible. The project team has identified most of these needs prior to the review, apart from the committee’s recommendation for two full-time staff for classical and AO-related systems engineering (rather than one).
- There is a need for stronger support to develop the science case and science requirements, including support for the science team lead and expansion of the NSAT to include junior members.
- There is a need for more formal approach to requirements management, performance budgeting, and interface control.
- High-performance open-loop AO is essential to the full success of NGAO, but it is not yet an established technology. The project should not under-estimate the ongoing effort that will be needed for analysis/simulation, design development, prototyping, and system integration/test in this area.

Our detailed comments on these topics (and some others) are given below, organized according to the elements of the committee charge and the supporting questions outlined in our instructions.

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 complete and compelling?***

The science enabled by NGAO is very compelling. At its predicted performance level, NGAO represents a striking improvement over the existing Keck AO system, which is already the "gold standard" of a high-impact, highly demanded, and highly replicated science instrument on Keck II. With dramatically improved sky coverage, NGAO will represent a paradigm shift by extending the applicability of LGS AO to routine use for nearly **any** science program at near IR wavelengths (> 0.8 μm) that requires only a modest field of view (< 30 ″) or single-object spectroscopy. With major gains in Strehl ratio, NGAO's image quality will rival and typically exceed space missions. As such, NGAO represents a major step forward. The predicted performance of NGAO leaves little doubt that its advantages in various areas are demonstrable and significant with respect to existing AO systems, other planned AO systems on 8-10-meter class telescopes, and even JWST.

Taken as a whole from a range of different documents made available to the committee, the science case is extensive and includes much important science. The committee understands that these cases were selected to cover the range of required capabilities for a particular type of AO instrument, not necessarily the full range of enabled science. Even so, we find that few, if any, vitally important cases have been entirely neglected. Although the science case for NGAO is strong, it is currently dispersed among several different documents, and it is presented in varying amounts of detail. To consolidate the science case and to maximize the scientific community's knowledge of NGAO's strong potential for scientific impact, we offer a range of suggestions for the future direction of the science effort:

- We recommend that the senior scientist assigned to the science case be paid or supported, if possible, with the continuing task of fully consolidating the cases and including simulations and the addition of detail where necessary.

- We recommend a larger, well-supported, core *standing* science team with a mix of junior and senior scientists to provide support. The Observatory should consider allowing the team an allocation of Keck LGS engineering time as a testbed for key scientific ideas and questions. This time would be used to address technical questions that arise from the development of the NGAO science case.

- We recommend that the project consider specific community engagement events, such as a special session before, after, or during the Keck Science Meeting that is specifically aimed at publicizing and exploring the potential for scientific breakthroughs with NGAO. A public webpage for updated information on the status of NGAO and its science case would also be very effective.

- We suggest that some comparisons of NGAO performance and capabilities with respect to other observatories and instruments could be made more quantitative. Simple simulations showing the relative performance of NGAO against other systems are extremely useful, such as the simulation of a high-redshift galaxy shown in the SCRD (Section 2.1, Figure 3), the reconstruction of kinematics around a black hole (SCRD Section 2.2, Figure 7), or the comparison of stellar orbits in the Galactic Center (SCRD Section 2.3, Figure 9). It would be useful to have these types of high-impact figures available for all of the major science cases, preferably consolidated into a single document with the specific, limited (and explicitly stated) aim of communicating scientific

- The committee believes that it is unnecessary to compare NGAO against TMT scientifically. We recommend a focus on its complementary properties, such as (1) its long lead time over TMT, (2) the fact that it affords a larger fraction of UC and Caltech access, and as a result, (3) its ability to support larger projects in the era of TMT.

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?***

The Science Case Requirements Document and the Observing Operations Concept Document look generally complete and well documented.

- ***Is a clear flow down established from the science requirements to the technical requirements?***

The requirements flowdown in the Observing Operations Concept Document is generally well developed for most high-level technical requirements including wavefront error, tip/tilt, Strehl, encircled energy, and operations modes, etc... The flow down for some of these requirements is not always quantified (for example the PSF reconstruction). We also note that the stray light budget is missing.

The flow down matrix presented by Peter Wizinowich during the review helped considerably in understanding the flow down from each science case to each high level technical requirement. We recommend including such a matrix (with proper backup) in any funding proposal.

- ***Are the performance and error budgets complete and consistent with the science requirements?***

Most performance and error budgets were presented as Excel spreadsheets, and the stated results were generally consistent with the science requirements. Spreadsheet budgets are a useful tool, but a more formal and consolidated presentation would have been desirable for a design review. Specific assumptions and models were sometimes difficult to identify and evaluate without searching through the formulas in individual cells. More work is also necessary at a lower level for bottoms-up validation of some of the budget terms, for example misregistration, WFS spot sizes, LOWFS tip/tilt performance, etc. It may be possible that some additional information is available in the Contour database, but the committee did not have access to the database.

- ***Are the technical requirements clear, complete and well documented?***

The system-level technical requirements are summarized in Keck Adaptive Optics Note KAON-771. The description of some requirements is fairly brief, but the overall description is at a preliminary design level. The committee was not able to find fully documented technical requirements at the subsystem level. Many of the overall AO technical requirements were described in the Preliminary Design Wavefront Error Budgets document KAON-716 (e.g. order of AO correction or WFS detector read noise), but the lower level technical requirements for subsystems were not. We believe that some or all of these requirements are defined in the Contour database, but we were not able to access it.

The proposed methodology for defining the interface requirements is questionable (for example, mechanical and optical interface definition within Solidworks and Zemax), especially when sub-contractors are involved. We recommend that the team provide more attention to formal requirement and interface definition during the detailed design phase.

As the project grows in scope and the project team expands, a more structured approach to document management may also be needed. The review panel found it difficult to effectively navigate through the available documentation, though the project team seemed to know where everything was. The Contour database may provide the required tools; if so, it should be widely accessible (read-only) within the project team and (we suggest) to future reviewers. It may be necessary to expand the contents of the database.

3. Evaluate the preliminary design for technical feasibility and risk, and assess how well it meets the scientific and technical requirements.

Roughly 2/3rd of specifications are still TBC/TBD until the Detailed Design phase, but here are our preliminary answers.

- ***Does the performance predicted for the design meet the scientific and technical requirements given in the System Requirements document?***

The overall performance and error budgets generally meet the requirements, but many terms in these budgets remain top-down allocations. Many of these terms (calibration accuracy of open-loop AO, LOWFS performance on actual asterisms, correction of optical alignment and fabrication errors by AO, etc.) require further validation to confirm that the requirements can be met. This validation effort may include additional simulation/modeling, prototyping and lab/field tests, and development of detailed designs.

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

The work presented at the review indicates that the predicted performance *does* meet the scientific and technical requirements. Further effort is needed to provide greater certainty. The proposed work for (i) additional AO simulation and analysis, and (ii) more detailed opto-mechanical design in the Detailed Design phase is appropriate. Work on PSF reconstruction and tests of such reconstruction deserve a particularly high priority, since much of the science relies on accurate PSF estimates rather than uniform PSFs. This work should proceed as quickly as possible, even if full funding of the Detailed Design phase is delayed.

The project should also be willing to consider limited performance de-scopes when necessary.

- ***Does the design appear feasible?***

Compliance with many requirements is still TBD until the Detailed Design phase, but the committee feels that the design is likely feasible with sufficient care and attention to the detailed design. Some areas of particular concern we identified were:

- Partially open-loop adaptive optics: The committee feels that the open-loop AO aspects of the system *can* work, but much more effort will be needed to confirm that they *will* work. The budget allocations in the WFE budget must be translated into subsystem requirements, and designs developed that confirm these requirements will be met.

- Calibration strategy: Much work remains to be done in this area during the detailed design phase. Are the necessary FTEs allocated to this task? This would be a good task for the AO scientist and/or operations scientist. The work should begin soon, because we believe that there is a significant impact on the RTC design, at least for the mid-level SW.

- RTC design: The committee is not yet convinced that the RTC is at a Preliminary Design level. A considerable amount of design work has been done, as described in the dedicated KAONs and also during the presentations. However, further design improvements may be necessary, in particular for

- Control software: The committee believes that the control software is at a preliminary design level overall. The decision to use/modify the ATST Common Software infrastructure for NGAO will be revisited during the next phase of the project, which is reasonable since the software lead has changed. The overall scope of the control software is well defined, except for the ownership of the so-called “background and optimization processes” which compute and update the parameters for the RTC hard real time processes at a slow rate. These processes are not within the scope of the RTC, but they do not seem to be included in the AO control software either.

- Opto-mechanical design: More work is needed to confirm that the expected alignment stability is compatible with open-loop AO requirements. In particular, regarding the alignment of DAVINCI to KNGAO, it seems very possible that some sort of on-instrument WFS may still be required for flexure compensation.

- LGSF: This is a well developed design and generally at a PDR level, but the FEA thermal/gravity analysis, alignment tolerances, and wavefront error budgets need to be further developed early in the Detailed Design phase. The interface of the system with the telescope top end also requires further definition. Since the system appears to comply with the throughput requirement very easily, it may be worth checking whether a tighter but still feasible requirement would provide enough overall performance improvement to be justified.

- The general level of complexity is necessary, but a potential source of risk.

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

The top-level risks appear to have been identified and characterized, with the exception of the risk due to the overall system and project organization complexity, which is a risk in and of itself. This risk is partly mitigated by the experience and close collaboration of the senior members of the project team, but further mitigation requires more rigorous approaches to requirements development/documentation (outlined above), project management, and systems engineering (outlined below). It is also mitigated by matching the top-level WBS elements to groups at specific sites, as has been done.

It could be argued that the programmatic risks due to management structure (#6 on PowerPoint slide) and lack of full-time personnel (#5) have been underestimated both in terms of likelihood and impact. The assumption that all the missing personnel can be in place 6 months from the start of the Detailed Design phase is questionable, particularly for the science staff.

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

The risk mitigation efforts are likely to result in the retirement of critical risks, provided they are pursued in a timely fashion. In particular, the project should be cautious about proceeding with the design in areas where performance budgets are incomplete or where further simulations or tests are needed to better define the requirements. A system-level review by the project to examine interactions between subsystems (for example, the impact of calibration procedures on the RTC requirements or design) should be done at the start of the Detailed Design phase, if not sooner. This could be a good way for a newly-hired systems engineer to transition into the project.

Hiring the key full-time personnel identified by the project (and confirmed as necessary by this panel) as early as possible is a key to risk reduction.

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?***
`

A detailed bottoms-up cost estimate has been prepared for the completion of the project and for each major phase, including identification of contingency at the level of 25-30 % and annual inflation of 3.5 %. However, the effort for some items seems to have been under-estimated, for instance the effort required to develop & validate in the laboratory and on-sky a robust AO calibration strategy for NGAO. We believe that the development cost for the RTC might be larger than anticipated by the team, especially for the software development. To limit that risk we recommend organizing a dedicated RTC requirement "mini-review," in particular to contain the software development cost increase.

Although provisions for spare parts seem to be included in the NGAO cost, the spare approach for the laser may need to be re-assessed depending on the NGAO availability expected from the community. A failed laser might need to be shipped back to TOPTICA for repair and not be available for some time. The absence of budgeted activities addressing tomographic reconstruction accuracy (beyond monitoring external activities) is also seen as a risk for this project

We understand from the team that labor costs of the the new key staff planned for the project are already included in the NGAO budget. These include the Project Manager, Systems Engineer, and project scientist. The AO physicist recommended later in this report is not currently included in the budget.

- ***Is the methodology used to develop the cost estimates sound?***

The cost estimate has been built using spreadsheets based on the TMT cost book approach. Spreadsheets have been developed following the NGAO WBS for each phase of the project. FTEs have been evaluated using Microsoft Project. Overall the methodology used is appropriate, although some WPs may need to be reviewed by the project office to reach the same level of confidence as the remainder of the WPs. In particular, the cost of the Wavefront control system, DM, and MEMs are only engineering estimates from verbal quotes with a limited level of contingency (11%).

- ***Is the proposed schedule to completion realistic?***

The schedule presented at the review is well developed and detailed, but is very success oriented for the Detailed Design phase, particularly since the project needs to consolidate the NGAO design at a system level and define more accurately the key system requirements and interfaces. Some time will also be required to recruit the high quality key personnel needed to develop this challenging facility. The FSD phase of 2 years is definitely very aggressive, considering the level of complexity of NGAO and the current level of technical maturity of several key components at PDR: LGS wavefront sensor, RTC, low order WFSs, and control strategy. The laboratory integration phase of 6 months is unrealistic by a significant factor (possibly 2-3), considering that the team agrees that this facility should not be installed at the telescope before lab demonstrations confirm that it is fully functional and up to specifications.

We recommend consolidating the overall NGAO schedule (i.e,, build schedule contingency explicitly into the schedule) in order to evaluate the actual cost increase due to a longer development schedule.

- ***Is the proposed budget to completion realistic?***

The budget presented looks realistic but remains tight, considering the potential risk of schedule slippage mentioned above. Some contingencies are built into the NGAO budget to cope with this possibility, but special care will be required to keep the project on track.

- ***Is there sufficient management reserve (contingency) allocated in the proposed budget to completion?***

The current level of contingencies is 24% for NGAO, 30 % for DAVINCI and 3.8% for cost escalation due to funding delay &/or schedule slip. These are appropriate at project level. However, the final distribution of these contingencies may need to be allocated differently than expected. In particular, cost escalation due to funding delays may be higher than expected. Contingencies for project management and systems engineering are relatively low (10% and 16%) for the FSD phase, and do not provide much margin for schedule slippage.

For that reason, we recommend that all contingencies be centrally managed by the Project office and used optimally for the benefit of the NGAO project.

We note that the overall contingency of NGAO seems consistent with the overall TMT AO contingency at the level of 1%.

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 (detailed 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?***

During the preliminary design phase, the project organization relied heavily on a distributed and collaborative approach to management, development and systems engineering. Key individuals filled multiple roles within the organization. In particular, Peter Wizinowich was tasked with overall Project Management, was also Project Manager of the WMKO Project group, and was involved heavily in the systems engineering efforts and a member of the Change Control Board. Wizinowich also participated in fund raising and other "external' efforts. Other core members of the management team included Claire Max, Rich Dekany and Don Gavel for NGAO and Sean Adkins for DAVINCI. Under this structure the project has made impressive progress in advancing the design of NGAO to a PDR level of development and put the project on a good footing to move forwards towards Detailed Design.

- ***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?***

The project recognizes that the ramp-up during the Detailed Design phase will place increased demand on Project Management, necessitating changes to the organizational structure. Systems engineering is one area that the committee has identified that needs to be significantly strengthened. Up to now, this activity has been distributed across the project with no one person having principal responsibility. The proposed new organizational structure includes the hiring of a full-time Systems Engineer. The committee feels that there are actually two distinct needs to fill in this area, however. The first is for a scientist/engineer ("AO Scientist") with a high level of AO expertise, who is cognizant of all aspects of the technical program and can provide competent advice to the project teams. The second function is for a person ("Systems Engineer") to implement and manage the formal systems engineering controls of the project (i.e. requirements generation and flow-down, error budgets, interface control, configuration control). The skills required for these activities are different and the committee believes that both full-time positions should be filled early in the Detailed Design phase.

The Systems Engineer will require assistance to perform the modeling efforts that are part of the charge of the SE group. Some of this may be provided by the AO Scientist if the right person is hired.

The project also proposes to hire a Project Manager for the WMKO NGAO group to off-load those duties from Wizinowich, and to allow him to concentrate on the high level project oversight and management. Wizinowich's new title will be Principal Investigator. At some later point in the Detailed Design phase the new WMKO NGAO manager may move up to support Wizinowich as the NGAO Project Manager.

The project also plans to hire an Operations Development Scientist whose duties include:
- Ensuring the science operations success of project;
- Leading development of science ops tools;
- Leading on-sky system characterization, science verification, and transition to operations.

The proposed strategy for organizing the second-tier project leads by institution rather than strictly by subsystem was also discussed by the committee. Such an approach can be successful, provided that the lines of communication between groups are maintained at all levels, and that appropriate systems engineering control is exercised.

The committee endorses the proposed organizational structure with the above changes.

Secondly, the project has implemented a set of management tools. The committee finds that:

Work Breakdown Structure: A WBS with sufficient detail has been developed for the remaining phases of the NGAO Project. The WBS dictionary is incorporated into the cost sheets (below).

Scheduling: Microsoft Project is being used for developing the schedule and generating spending profiles. MS Project is not a high end Project Management system, but is acceptable for a project of this scale as long as its limitations are recognized. In particular, budgeting should be accounted for outside of MS Project. The Project intends to begin tracking actual expenses versus the baseline budget. Earned value may be better tracked with other tools.

The schedules are success oriented. The project realizes that they still need to be scrubbed to check for completeness, level resources, identify tasks that can proceed in parallel, and add schedule contingency.

Cost Estimating: NGAO's cost estimating process is based upon a formalization borrowed from the TMT Project. These tools provide a traceable means for recording costs that roll up into the total project budget. The cost sheets also provide estimates of risk and associated contingency. A random sampling found no missing sheets.

The labor costs for NGAO are estimated at an Engineering Estimate (EE) level of confidence. Costs for around 50% of the non-labor items for the Detailed Design Phase are at a higher level of confidence. The estimates are informed to large extent by the prior experience of the project teams building predecessor AO systems. The overall cost estimate is reasonable with the proviso that there is little schedule contingency for potential delays that could result in added costs.

The cost sheets roll up into the MS Project schedule. Contingency is accounted for and allocated separately. The cost sheets will be updated as the costs are refined.

Risk Management. The Project Manager provides risk evaluation and tracking using standard tools which rank risks in terms of probability and impact. A good assessment of risks has been made. This review has identified additional programmatic and technical risks that should be added to the lists for these categories.

Change Control. The project has recently begun placing key documents under change control, and a Change Control Board has been formed. The change control procedures were not presented in detail.

Interface Control. Interfaces are currently maintained with global documents. This is a risky strategy, subject to lost requirements and confusion between groups, and particularly a concern for such a distributed effort. An early charge to the Systems Engineer should be to identify key interfaces between major subassemblies and the control system, and to pull together requirements into the relevant ICDs.

Requirements Tracking: Requirements are tracked through the Contour data base. Compliance checking is employed. As noted above, the committee was not able to sample the detailed contents of the data base.

The committee endorses the management approach proposed by NGAO with the additional changes above.

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?**

The currently envisioned NGAO system successfully optimizes the delivery of new science. Many key questions from a broad array of sub-disciplines (ranging from the solar system all the way to extra-galactic) can be addressed with a next generation AO system that both increase the sky coverage for AO observations and has significantly smaller wavefront error. The latter will enable much higher Strehl ratios at the wavelengths currently used to perform AO observations, as well as workable Strehl ratios for the first time at shorter wavelengths. While most planned AO systems have currently optimized one or the other quantity (e.g., wide-field low, order systems that have improved sensitivity but low Strehl, or narrow field, high-contrast systems), Keck's NGAO system architecture provides a unique and powerful combination of sky coverage and performance, which will likely give it the widest scientific reach of any AO system in the upcoming decade. The team has successfully queried its user community for desired future AO capabilities, and designed a system that maximizes the match between science needs and the available budget through a build-to-cost exercise.

The team has done a good job of identifying several key pieces of the system that can be implemented early on in a staged way to provide both early science return and reduce the overall risk of the project. This includes the funded programs to implement a center launch telescope on Keck 2, the collaboration between ESO, AURA, GMT, TMT to fund and share the results of preliminary design reviews of a possible NGAO laser from two vendors, and the collaboration with Gemini and U. Groningen on PSF estimation (with a subcontract to Laurent Jollisaint for the first year of a three year program) Further early projects that have been submitted for funding include the procurement of a laser suitable for NGAO (MRI) and non-AO corrected NIR tip-tilt sensors (ATI). Other staged implementation options include the demonstration of the PSF reconstruction capability for LGS AO both on-axis and (with the help of the donated and implemented TMT site monitor) off-axis, and vibration reduction with a fast tip-tilt mirror. The review panel applauds these efforts and encourages the team to continue to identify any other pieces that can be done collaboratively.

NGAO is critical to the future success of Keck. By implementing laser tomography and AO-corrected NIR tip-tilt sensing, NGAO allows major improvements in performance (wave front error) and sky coverage, respectively. These two advances are essential for Keck to remain competitive in the future AO landscape. The schedule is set to deliver science within five years, but this is likely too optimistic. Ideally, this system will go online while JWST is operational, significantly before TMT, and at least one year before the closest approach of S0-2, the short period star at the Galactic center (i.e., by 2016) or these measurements will not be possible for another 15 years)

Ideally, this project would not be done in a phased or de-scoped manner. Only one possible phased approach was presented by the project team. This plan was to implement laser tomography first with the system's launch telescope, one 25 W laser, fewer LGS, fewer LGS WFS & LOWFS, no MEMS or open loop control, no new instruments, and an uncooled enclosure. This would provide higher Strehl ratios from improved laser power and reduced focal anisoplanatism. However, this approach would also result in additional periods where AO capabilities were unavailable as later phases were implemented, and would impact the science reach in at first light. It is not clear what this impact would be, since science trades have not been made. It is also not clear what budget implications such a phased approach would have.

A second, less drastic, de-scope option suggested by some committee members is to reduce the order of correction for the MEMS in the on-axis science path from 64x64 to 32x32. This would reduce the laser power and RTC processing requirements, and also relax the optical alignment tolerances to successfully implement open loop AO. The principal performance impacts would relate to the science cases requiring high contrast imaging.

We strongly encourage Keck to avoid either de-scope of this project.

7. Gauge the readiness of the project to proceed to the detailed design phase.

- ***Has the project adequately defined the objectives, work breakdown structure and task plan for the next design phase?***
-

The overall objectives are appropriate for a Detailed Design phase, and the WBS is comprehensive. The project has identified the need for greater emphasis on a variety of tasks which did not achieve full attention (or were not completed) during the Preliminary Design phase, including:

- Requirements and interface definition
- Science operations planning
- Open-loop AO calibration strategies
- AO control software and the RTC design
- Opto-mechanical analysis for validation of open-loop AO performance budgets
- Additional AO modeling support for items 3-5 above

- ***Is the technical design sound?***

The readiness of the project for the next phase is not exactly a question of technical soundness, but is more the level of maturity which has been achieved. Most aspects of the design have reached a PDR level, with some exceptions already noted in response to question 3 above: quantitative performance of open-loop AO and the associated calibration strategies, RTC design, and FEA analysis of subsystems with critical/difficult stability requirements.

.

- ***Is the design concept and architecture adequately documented?***

Most aspects of the overall design concept and architecture (as distinct from the details of the design) are adequately documented. The lack of preliminary ICDs (which can be considered part of the architecture) is a concern for some members of the committee (see responses under 2, 4 and 5, above).

The RTC design shows a great deal of work and has been documented at length, but the committee had some difficulty grasping the overall concept and the hardware architecture within the time provided. This includes the relationship between the RTC and the AO control software. More detailed aspects of the design which were also not clear to us included: the design for the DM command generation module (number of GPU boards), the design of the Point and Shoot HOWFS module (again, the number of GPU boards per sub-system), and the interfaces between the tomography engine and the DM command generation module, for example.

Some aspects of the design/architecture are not adequately documented because they are not yet fully specified. This includes a complete approach to open-loop AO calibration and the PSF reconstruction algorithm.

- ***Are the resources identified for the next design phase sufficient to address the scope of work?***

The overall level of staffing appears to be sufficient, provided that the additional positions proposed by the project (and our suggestions outlined in section 5 above) are filled early in the Detailed Design phase. The two year schedule for this phase is very aggressive, and the staff assigned to the project will need to be shielded from distractions or other commitments. The project should review the level of effort estimated for some specific tasks, including the RTC programming/prototyping and “classical” systems engineering activities.

Individual Review Comments:

Jay Elias:

1. The panel understands the decision to use a visible wavelength acquisition camera as opposed to a near-infrared camera, but the project should recognize that this will impose additional operational burdens for some science cases. The project should explore more active approaches to identifying appropriate NGS as NGAO development proceeds. Such efforts could include pre-imaging on smaller telescopes and early access to preliminary survey catalogs. This is a problem that will not solve itself, though an immediate solution is not needed.

Brent Ellerbroek:

1. Given the amount of material to be covered, the project may wish to divide the Detailed Design Review into 3-4 smaller reviews:
   a. DAVINCI
   b. LGSF
   c. AO Bench
   d. Full NGAO system, emphasizing the flowdown of requirements, performance verification, and the software/control systems.

   Each of these major subsystems may benefit from 1-2 interim reviews in addition to a final review.

Matt Johns:

The specification for maximum acceleration due to earthquakes has been set based on Keck's location in seismic Zone 4. Recent studies by a number of projects have shown that this method can produce unrealistically low values unless amplification within the telescope structure is taken into account. This involves a dynamic response analysis and may require a site specific seismic hazard analysis to determine the power spectrum of ground accelerations at the site. Amplification of ground acceleration by factors of 2 or more are possible depending on position within the structure.

Operational level (OLE) and Survival level earthquakes (SLE) are typically estimated for recurrence periods long compared to the expected lifetime of the facility. For GMT these are 200 and 500 years respectively but might be shorter for an instrument with a shorter expected lifetime. A 200 year return period has a 10% probability of occurrence in 20 years. The fact that Keck recently survived a large earthquake is good news but no guarantee that it will not experience a larger one in its lifetime.