Summary of NGAO Trade Studies

KECK ADAPTIVE OPTICS NOTE 495

Christopher Neyman
June 20, 2007
Updated March 10, 2008

1. Introduction

The Keck Next Generation Adaptive Optics (NGAO) project originally planned for 29 trade studies[1] to explore, in more detail, design issues that were raised before the system design phase of the project started in October 2006. A summary of each trade study including WBS, trade study name, and status is given in (see page 2). The overall plan for the systems design phase of NGAO was revisited in April of 2007; see KAON 481 [2]. As of result of this planning activity, several trade studies were cancelled. Two new trade studies were added to the NGAO plan: 3.1.2.1.1.16 deployable IFU & LOWFS AO & Object Selection and 3.2.3.5 Uplink AO. These two trade studies are now completed. The 3 originally planned trade studies which were still ongoing in June 2007 have been absorbed into the optical design report, KAON 549. The other 15 trade studies are discussed in this report. This report was updated in March 2008 with the final status of these studies.

2. MOAO & MCAO

This is a research area for current AO technology; as such this report can only provide a brief summary. More details and discussion are provided in the KAON 452[3]. The study author lists the following as his top-level conclusions.

The science advantages of MCAO are:

1) Contiguous AO-corrected field of view
  a. Choice of PSF stars in the field
  b. Higher packing density of IFU pickoffs
  c. Very extended objects: Jupiter, Saturn, Uranus rings
  d. Long exposure of hi-Z field galaxies
2) DMs in closed loop, eliminating DM calibration error and drift

The science disadvantages of the MCAO architecture are:

1) Higher field-dependent anisoplanatic error than a MOAO system
2) Extra surfaces in the relay contribute to background emission and reduce throughput.
3) DMs in series could distort the contiguous field randomly resulting in higher astrometric error.
4) Front-end relay adds field and zenith dependent distortion and aberration into the LGS beams, which even if pre-calibrated, will introduce some amount of wavefront error to the science beams via the closed loop.

The science advantages of MOAO are:

1) Lower isoplanatic error at the science field points
2) MOAO units are deployable on a wider field of regard than MCAO, sky coverage is enhanced by correcting tip/tilt stars with their own MOAO units, allowing dimmer tip/tilt stars than with MCAO.
3) Reduced number of optical surfaces for AO correction that minimizes emissivity and optimizes throughput
4) No field distortion introduced by DMs in series.

Table 1: NGAO trade study WBS and status

WBS	Title	Status (3/10/08)	Comments
3.1.2.1.1.1	MOAO & MCAO	**Completed**	KAON 452
3.1.2.1.1.2	NGAO Versus Keck AO Upgrades	**Completed**	KAON 462
3.1.2.1.1.3	Adaptive Secondary Mirror Option	**Completed**	KAON 485
3.1.2.1.1.4	K & L-band Science	Cancelled	See KAON 501
3.1.2.1.1.5	Keck Interferometer Support	**Completed**	KAON 428 and 483
3.1.2.1.1.6	Instrument Balance	Cancelled	Observatory issue
3.1.2.1.1.7	GLAO for non-NGAO Instruments	**Completed**	KAON 472
3.1.2.1.1.8	Instrument Reuse	**Completed**	Posted to Twiki
3.1.2.1.1.9	Telescope Wavefront Errors	**Completed**	KAON 482
3.1.2.1.1.10	Observing Model	**Completed**	KAON 476
3.1.2.2.1.1	AO Enclosure Temperature	Cancelled	Part of AO enclosure design
3.1.2.2.1.2	Optical Relay Design	**Completed**	See KAON 549
3.1.2.2.1.3	Field Rotation Strategy	**Completed**	See KAON 549
3.1.2.2.1.4	Dichroics and Beamsplitters	Cancelled	See KAON 549
3.1.2.2.1.5	Rayleigh Rejection	**Completed**	KAON XXX, see draft v0.5
3.1.2.2.1.6	LGS Wavefront Sensor Type	**Completed**	KAON 465
3.1.2.2.1.7	LGS Wavefront Sensor Number of Subapertures	**Completed**	KAON 465
3.1.2.2.1.8	Slow Wavefront Sensor	Cancelled	
3.1.2.2.1.9	Low Order Wavefront Sensor Architecture	**Completed**	KAON 470 and 487
3.1.2.2.1.10	Number and Type of Low Order Wavefront Sensors	**Completed**	KAON 470 and 487
3.1.2.2.1.11	Centroid Anisoplanatism	Cancelled	
3.1.2.2.1.12	Deformable Mirror Stroke Requirement	Cancelled	
3.1.2.2.1.13	Stand-alone Tip/Tilt Mirror vs. DM on Tip/Tilt Stage	Cancelled	
3.1.2.2.1.14	Correcting Fast Tip/Tilt with DM	Cancelled	
3.1.2.2.1.15	Focus Compensation	Cancelled	
3.1.2.1.1.16	d-IFU & LOWFS AO & Object Selection	**Completed**	KAON 562 & Team Meeting 6[1]
3.1.2.3.1	Laser Pulse Format	Cancelled	See LAO Twiki
3.1.2.3.2	Free Space Versus Fiber Relay	Cancelled	See Keck I LGS upgrade
3.1.2.3.3	LGS Asterism Geometry and Size	**Completed**	KAON 429
3.1.2.3.4	Variable Versus Fixed LGS Asterism Geometry	**Completed**	KAON 427
3.1.2.3.5	Uplink Compensation	**Completed**	KAON 509

[1] See Team Meeting 6 presentation by Anna Moore
http://www.oir.caltech.edu/twiki_oir/bin/view/Keck/NGAO/070418_UCSC_NGAO_Meeting_6

Science disadvantages of the MOAO architecture are:

1) Discontinuous field of view hampers crowded field studies, e.g. contamination by nearby stars' seeing halos, which are not imaged and so, cannot be PSF subtracted.
2) Cannot image large extended objects
3) DMs are open loop controlled and are thus subject to calibration and drift error.

The MCAO architecture has the following implementation advantage:

1) AO control of DMs is closed-loop, allowing feedback of mirror shape to the control system.

MCAO has the following implementation disadvantages:

1) Powered relay optics and DMs not conjugate to the ground must be larger diameter than a DM at a pupil.
2) The AO relay introduces non-common-path aberration and pupil distortion and may force custom design of the wavefront sensor optics to compensate. The custom optics may need to have moving components in order to track sodium layer distance change with zenith angle.
3) Pupil size has a lower limit set by physical optics. This size is larger than MEMS DMs produced today

The implementation advantages of MOAO are:

1) MEMS are small, enabling the AO systems to be tucked into instruments, making them ideally suited for compact MOAO units.
2) MEMS are low cost. The marginal cost of scaling to high actuator counts is considerably lower than that for large DMs. For the BMC devices, this number today appears to be around $200-300 per actuator as compared to about $1500 per actuator on a piezoelectric deformable mirror. The low cost makes it practical to have a spare on hand.
3) "Go-to" repeatability – A major advantage of an electrostatic actuation over piezoelectric actuation is the absence of hysteretic effects in the displacement to voltage response curves. This implies that the devices could be driven open loop to given surface deflections.
4) The low cost and small size of MEMS DMs opens up the possibility of "ubiquitous MEMS," i.e. devices sprinkled throughout the system to elegantly solve tough optical problems.
    a. MEMS DM in each wavefront sensor: This creates a mini closed loop AO system in which the wavefront detector is kept near null, where its linearity properties are best. The predictable voltage response of the MEMS allows it to be used as the probe of the grosser portion of the wavefront shape, which would be added to the wavefront sensor's residuals to complete the wavefront measurement. A variant of this is to use MEMS DMs to correct for the slowly varying but known non-common path aberrations of LGS wavefronts.
    b. MEMS in the tip/tilt sensors: If there are enough degrees of freedom to form diffraction limited cores at the sensing wavelength, fainter guide stars can be used to sense tip/tilt to a given accuracy because centroid error is proportional to the spot size and inversely proportional to square root of brightness. The ability to use fainter guide stars would give us higher sky coverage.

Practical disadvantages of MOAO are:

1) MEMS stroke dynamic range may not be adequate to correct the whole atmosphere, leading to a requirement for dual-mirror "woofer-tweeter" MOAO units. The latest generation of MEMS mirrors under development (a 4000 actuator mirror for the Gemini Planet Imager AO system) should have just enough mechanical stroke to cover 5-σ wavefront variation for the Keck 10 meter tip/tilt removed wavefront.
2) MEMS mirrors have not been shown to work yet in astronomical instruments (this is a risk issue)
3) High-order MEMS are presently available from only one manufacturer (another risk issue)

3. NGAO verses Keck upgrade

The authors of this KAON[4] conclude that a Keck AO upgrade is worth further consideration. Implementation options range from an incremental approach, delivering new science capabilities along the way, to a single implementation effort without the interim disruptions to science.

The pros and cons for a Keck AO upgrade include:

1) Pro - Potentially a lower cost. However, as the costs are further evaluated, they would likely increase.
2) Pro - The interferometer's needs are addressed. This will be a difficult problem for NGAO and might require a complete reconfiguration or AO systems.
3) Con - Likely lower performance ultimately than NGAO
4) Con - Only two science instruments (possibly 3) could be available at any one time, unless the other telescope is also upgraded. Unclear yet how many simultaneous instruments could be offered by NGAO.

A Keck AO upgrade would allow for an incremental approach. The pros and cons for an incremental approach include the following.

1) Pro - Some performance improvements could be available sooner.
2) Pro - The system could be improved as funds became available.
3) Pro - It also might allow for and address the need for periodic replacement and maintenance (and the funds to support these) that could be done as the same time as the upgrades.
4) Pro - This approach doesn't require as much of an all or nothing risk. Although this risk could be mitigated for NGAO, there is the risk that we would not have the funds to complete the system.
5) Con - Periodic shutdowns would be required which would make the system unavailable for science, although a one-time shutdown might take a substantial amount of time if NGAO is installed in one step.
6) Con - Increases the risk to operations due to a system always under development.
7) Con - Increases the risk to the development team schedule from potentially needing to support an operational system.
8) Con - Adds a constant stress to the development team.

4. Adaptive secondary mirror options

The author of this study[5] notes the following points regarding the use of an adaptive secondary mirror.

1) An ASM offers the lowest emissivity and highest throughput option to the science instrument since it is no longer necessary to have a separate tip/tilt mirror or to re-image the telescope pupil onto a deformable mirror (at least 4 reflections are saved).
2) An ASM combines the tip/tilt, DM, and chopping roles all on the same mirror and therefore provides a more stable thermal background that is easier to subtract.
3) An ASM could potentially be used to replace one or more of the tip/tilt mirror, chopping, and DM roles for the existing AO systems (replace the DM with a flat?) if a Keck AO upgrade path were chosen.
4) There will still be the issue of picking off light for wavefront sensing and dealing with field rotation. A new issue is that the DM (ASM) will be rotating with respect to the wavefront sensing.
5) Space for a laser launch telescope behind the secondary mirror could be built into the ASM design, as opposed to design it into the existing secondary mirror module.
6) The use of an ASM could also allow the AO system to be physically smaller which might allow small field AO systems and science instruments to be placed at Cassegrain. This could also allow the existing AO systems to be left at Nasmyth to feed the Interferometer. Cassegrain would also be the best location for the near-IR deployable IFU since low emissivity is a critical requirement for the extragalactic science.

5. Keck Interferometer support

The authors of this study[6] state that no ideal solution has been found for supporting the interferometer with NGAO. The following points are noted about each option:

1) Swapping Keck I/II with NGAO
    - a. Hardware costs relatively low, compared to building new AO systems
    - b. Cost of moving NGAO is higher than fixed NGAO. This assumes the final design is similar to the proposal design.
2) Matching NGAO to Keck
    - a. Challenging to match polarization states
    - b. Likely requires NGAO relay with K-mirror and in plane optics
    - c. No broad wavelength solution found
    - d. Lower cost compared to other options, approximately 100K compared to millions
3) Two AO systems
    - a. AO secondary on each telescope
        - Elegant solution, but costly
        - Utility of a shared capability could offset higher costs
    - b. MEMs AO for each IF arm
        - Relatively inexpensive
        - Small footprint allows more mounting/packaging options

The lowest cost option but perhaps the most technically challenging will be matching NGAO to a legacy AO system. A more formal consultation with the Keck Interferometer team is recommended as a next step. Possible members to consult with should include Mark Colavita, Gene Serabyn, and Kent Wallace.

6. GLAO for non NGAO instruments

The author of this KAON[7] notes that it is clear that there are potential benefits, ranging from modest to significant, to non-NGAO instruments from a GLAO implementation. If a GLAO system for Keck was pursued (independently of NGAO), such a system would require the existence of an ASM and at least 4 LGS. These might be acquired as part of NGAO or as a separate project. Following the design of these subsystems, the next technical study should investigate the most efficient WFS implementation and look into the technical solutions that have the best cost/capability trade. New WFS modules could be built exclusively for each non-NGAO instrument that wanted to use GLAO. A simpler alternative might be building a single GLAO WFS module that could make GLAO available to all instruments at a given focus, e.g. all Nasmyth instruments or all Cassegrain instruments.

7. Telescope wavefront errors

The main results of this trade study[8] can be summarized as:

1) Full aperture tip tilt errors could dominate the tip/tilt error budget.
    a. Resulting in poor sky coverage
    b. "Encircled Energy Science" might be impacted less
2) Segment motion
    Acceptable error, comparable to NGAO June 2006 proposal and current error budget
3) Segment figures
    Acceptable error, comparable to NGAO June 2006 proposal and current error budget
4) Segment phasing
    Small, needs to be added to NGAO budget, interaction with figure errors not tested
5) Fast guiding on stars outside NGAO corrected field of view appears feasible

The trade study authors' recommendations would be

1) Perform additional analysis of the gains in tracking beyond the simple PI controller considered in this study. Examples would be parametric oscillator and Kalman filters.
2) Understand what might be done to reduce 29 Hz vibrations in telescope segments, secondary, and tertiary.
3) Continue to investigate ways to improve the segment figures. NGAO should leverage information from the TMT study of warping harness at Keck.

Based on this study, it appears that full aperture tilt needs to be given higher priority in the NGAO design and in mitigation efforts with the current Keck AO system. Other telescope wavefront errors appear to be accounted for correctly in the NGAO error budget. It would be advantageous to reduce 29 Hz vibration drivers such as pumps and motors even further, as this is cost effective compared to the cost of an additional "fast guider" for NGAO. The possibility of using seeing limited guide stars outside the corrected field of NGAO appears feasible and should be studied further than the simple scaling law analysis included in this report.

8. Observing model

The authors of this KAON[9] have presented a trade study for the NGAO observing models by first defining top-level goals for NGAO science operations. They then reviewed and discussed the existing classical and queue-service models from the published data. They have presented three case-study observing models to further assess a range of possibilities for NGAO. The authors recommend that the NGAO observing model be neither the lean-classical observing model nor the queue-service observing model and they recommend working with the Keck science community to develop a new flexible observing model (possibly phased) for NGAO.

The authors further recommend that the NGAO science operations strongly support the top-level goals that emphasize the need for high quality data products and our given estimate for that effort. They note that this will require designing and building an extensive suite of simulation and observing tools for the AO and the science instruments. It additionally requires the development of reliable and accurate calibrations methods for photometry and astrometry. This implies knowledge of the PSF across the science field of view. The authors note that a great deal of potential synergy exist between the Observatory and the community to support the science goals and minimize the implementation costs of observational tools.

9. Rayleigh rejection

The authors of this study[10] note that fratricide due to Rayleigh scatter is a serious issue for a 5 laser beacon AO system. It is ideal to use a 1-3 micro-sec pulsed laser to mitigate this problem. In the event of this not being available, and mode-locked CW laser being the only option, appropriate background subtraction, projection location, baffles, and stops are to be chosen. The authors note that the effect of fratricide still needs to be quantified more accurately via detailed simulations, though the current study has developed a preliminary model of this effect. The authors advise that NGAO use a center projection method for the LGS. The authors recommend that a safety margin must be included in the error budget to account for the short and long term fluctuations in Rayleigh scatter caused by variations in the atmosphere. Although laser collisions, which is observing through the laser beam projected from another telescope, are to be avoided, it does not actually render the data useless. The effect of a collision is comparable to the sky background at Mauna Kea in the V-band.

10. LGS Wavefront sensor type and number of subapetures (combined reports)

The authors of this study[11] recommend that if NGAO chooses to use a CW laser it is best to work with a Shack Hartmann WFS and a radial geometry CCD. Both technologies are mature (as compared to counterparts) and the advantage of pyramid WFS is only a few (less than 5 nm) nm in WFE as presented by current models. In the wide field cases, the majority of the error (288 nm) comes from tomography.

The authors of this study performed a benefit vs. cost (laser power) analysis using Rich Dekany's WFE spreadsheet with the general assumptions described in the report. Additional assumptions and parameters were used to simulate the science observing scenarios: the atmosphere used was based on KAON 303 and pixel charge diffusion was assumed to be 0.3 pixels for the Shack-Hartmann WFS case. With a pyramid WFS, the charge diffusion was assumed to be zero. The Shack Hartmann wavefront sensor charge diffusion and the AO spot size summed in quadrature was used instead of the lenslet diffraction spot size. No MEMS mirror based active correction of the spot size at the WFS was considered.

11. Number and type low order wavefront sensors

Based on the results obtained within this study [12], the authors make the following observations, notes and caveats:

1) Near IR sensing is preferable to visible for the NGS WFS. In particular, a combination of J+H bands gives the best performance.
2) Multiple TT stars can significantly improve the tilt estimate. A further improvement can also be achieved if one of the NGS WFS also measures focus, which aids in estimating the combinations of quadratic null modes.
3) A 2 arc min diameter patrol field for finding NGS is sufficient. There is little benefit to making the field larger due to the reduced partial correction and tilt anisoplanatism from being so far off-axis.
4) The radius of the LGS asterism affects the partial correction of the NGS and hence the sky coverage. The LGS asterism radius needs to be optimized as a function of a weighted sum of the tomography error over the science field and the residual TT error from the partially corrected NGS.

12. Low order wavefront sensor architecture

The authors make the following recommendation based on this study[13] and the previous one, see section 11.

1) 2 near-IR (J+H) tip/tilt sensors with built-in MEMS DM for image sharpening. These sensors may employ a STRAP type optical design adapted to a near-IR detector.
2) 1 near-IR (J+H) pyramid sensor with at least 2 by 2 sub-apertures and with a built-in MEMS DM for image sharpening.
3) At least 1 LGS dedicated to the LOWFS system for image sharpening.

The STRAP sensor (System for Tip/Tilt Removal with Avalanche Photodiodes, see e.g. Bonaccini 1997[2]) is mentioned here because it is a well documented and routinely used device that has optical properties in common with a pyramid sensor, making it interesting for the current study. It can be regarded as a lenslet-based 1 by 1 pyramid sensor (Bauman 2003[1]) without modulation. Given the superiority of the PWFS compared to the Shack-Hartmann implementation observed in simulations in the report, even in the 1 by 1 tip/tilt-only case, authors recommended a near-IR version of a STRAP type sensor as a preliminary option that could make a good candidate for the tip/tilt LOWFS. With a 2 by 2 PWFS in slope mode, the configuration listed above gives a total of 12 measurements which is enough to reliably resolve the first 9 tomography null-modes (and the authors of this study believed this to be sufficient, compare to KAON 470).

Although it drives up the cost somewhat, in the cost/performance trade-off it seems to make sense to provide for at least one LGS dedicated to the LOWFS system, in order to be always ensured of decent performance of at least one of the sensors. For each observing scenario, based upon the high order WFS asterism and the geometry of candidate low order WFS NGSs, one would direct the low order WFS dedicated LGS to the NGS that would benefit the scenario the most and have the remaining two low-order sensors drive their MEMS DMs from high order WFS telemetry using MOAO reconstruction algorithms. How such a decision matrix might look is beyond the scope of this study, but to a zero-order approximation, although potentially over-simplifying the situation, it might be an acceptable strategy to always use the low order WFS dedicated LGS for the 2 by 2 PWFS in order to ensure a minimum level of performance by this sensor.

13. LGS asterism geometry and size

The authors of this study[14] state that based on the science cases it seems clear that the quincunx asterism (5a) will be unable to deliver the required LGS tomography performance in all cases under the given seeing conditions. Barring relaxed requirements from the science cases or a substantial improvement of the average seeing on Mauna Kea, the NGAO system will most likely need to look to alternative asterism that can deliver higher performance levels. Taking into account the points made in sections 2.1, 2.2, and 2.3 of the full report, as well as the realism of having a finite budget for building the instrument, it seems like a reasonable recommendation that future studies and iterations on the NGAO performance budgets should look at asterisms having in the range of 7-9 LGS. The final choice should be deferred until much more comprehensive simulations have been conducted using a tool like e.g. LAOS [7], but as a starting point, this trade study nominates the three asterisms 7a, 8a, and 9c in the nomenclature of the original report.

14. Variable Verses Fixed LGS Asterism Geometry

The authors of this study[15] conclude that for a continuously variable laser guider star asterism:

1) There is little performance benefit in narrow field performance.
2) There is a significant performance benefit for d-IFU science when the mismatch between asterism and target radius exceeds 20 arc sec.
3) Cost overhead in optomechanical hardware is small.
4) Real-time and supervisory control software costs will dominate.
5) In addition, any laser launch costs that may arise due to a continuously variable asterism should be evaluated, as this was not part of the study.

Software and laser launch costs allowing, NGAO should assume continuously variable asterism in the system design.

15. Instrument reuse

The authors made the following conclusions from their study[16].

NIRC-2 as the NGAO Near-IR imager

1) This NGAO instrument requires excellent RWFE leading to exquisite imaging quality across the field of view. The NIRC-2 camera optics for all plate scales are not sufficiently high enough quality for this application.
2) Upgrading one or all of the camera channels is not sufficient or cost effective over designing a fixed plate scale imager from scratch.
3) The OSIRIS offset imager is an intriguing alternative and may be suitable for a first light Near-IR imager, especially in J and H, where the oversized pupil stop has less detrimental effect to sensitivity.

NIRC-2 as the L/M band imager

1) With an approximate 500k optics upgrade to the middle channel of NIRC-2, in addition to upgraded detector electronics, NIRC-2 could satisfy the requirements for the NGAO L and M band imager.
2) The optimum solution for this specific instrument is to incorporate a deformable secondary mirror feeding a Cassegrain mounted imager, designed from scratch.
3) The current M band performance of the Keck telescope combined with the AO system, including K-mirror de-rotator, is poor.

OSIRIS as the Near-IR IFU

1) As it currently stands OSIRIS does not fulfill the maximum field of view requirements of this instrument neither the K band background performance requirements at any of the pixel scale, nor the required resolution especially at the largest pixel scale (100mas).
2) If only the fine scales are required for OSIRIS it is possible to consider pupil stop improvements that reduce the amount of contaminating radiation that increases the measured sky background. A replacement of the grating may help increase throughput.
3) Designing an IFU spectrograph offering the large range of plate scales that is found in OSIRIS is technically quite challenging. Considering the incorporation of the coarse scale in the d-NIRI instrument, the science team is asked to justify the requirement of both the fine and coarse scales for the Near-IR IFU and therefore clarify the maximum field of view. If the 100mas scale is not required, or does not need to satisfy the requirements of background and resolution stated, then OSIRIS can be considered as a candidate for this NGAO instrument.
4) There may be some issue with implementing OSIRIS without a K-mirror de-rotator in NGAO.

16. Uplink AO

The purpose of this trade study (NGAO WBS 3.1.2.3.5) was to explore the advantages and disadvantages of adaptive optics wavefront control of the outgoing laser in order to correct for atmospheric aberrations on the laser uplink path. The main advantage of uplink correction is the possibility of obtaining a laser guidestar that is smaller in angular extent than one without compensation. Since the wavefront sensor is to first order dependent only on surface brightness of the guidestar, the smaller spot needs less total brightness which in turn implies less laser power is required to create it. With each Watt of laser power having a high marginal cost in the overall AO system, improvements that reduce the required power must be taken seriously.

It appears that if one takes pains to use the type of wavefront sensor that can take advantage of it, there is a potential for a very significant reduction of required laser power if the uplink beam is AO corrected. However, the total package, which involves the success of more than one untested technology, is of reasonably high technical risk. Still the benefit potential suggests that even if the more conservative approach is taken during initial design phases, development testing of the new technologies should proceed.

17. d-IFU & LOWFS AO object selection

The trade study report presented concept solutions for the Object Selection Mechanisms (OSM) for the interim Low Order Wavefront Sensor assembly and Laser Guide Star assembly. The report contains summary design for the LOWFS OSM and the LGS OSM. A list of the assumptions regarding acquisition and dithering was presented in section 4 of the report.

References

1. P. Wizinowich, R. Dekany, D. Gavel, and C. Max, “Keck Next Generation Adaptive Optics: System Design Phase Systems Engineering Management plan”, Keck Adaptive Optics Note 414 (W. M. Keck Observatory, Kamuela, Hawaii, 2006).
2. P. Wizinowich, R. Dekany, D. Gavel, C. Max, S. Adkins, and D. Le Mignant, “Keck Next Generation Adaptive Optics System Design Phase Mid-FY07 Replan”, Keck Adaptive Optics Note 481 (W. M. Keck Observatory, Kamuela, Hawaii, 2007).
3. D. Gavel, “Multi-Object Adaptive Optics and Multi-Conjugate Adaptive Optics Architectures System Design Trade Study”, Keck Adaptive Optics Note 452 (W. M. Keck Observatory, Kamuela, Hawaii, 2006).
4. P. Wizinowich, “NGAO Trade Study: Keck Adaptive Optics Upgrade”, Keck Adaptive Optics Notes 462 (W. M. Keck Observatory, Kamuela, Hawaii, 2007).
5. P. Wizinowich, “NGAO Trade Study: Adaptive Secondary Mirror”, Keck Adaptive Optics Notes 485 (W. M. Keck Observatory, Kamuela, Hawaii, 2007).
6. C. Neyman, V. Velur, J. Meguro, “Keck NGAO Trade Study: Keck Interferometer Support”, Keck Adaptive Optics Note 483 (W. M. Keck Observatory, Kamuela, Hawaii, 2007).
7. R. Flicker, “NGAO Trade Study Report: GLAO for Non-NGAO Instruments,” Keck Adaptive Optics Note 472 (W. M. Keck Observatory, Kamuela, Hawaii, 2007).
8. C. Neyman and R. Flicker, “Keck Telescope Wavefront Errors: Implications for NGAO,” Keck Adaptive Optics Note 483 (W. M. Keck Observatory, Kamuela, Hawaii, 2007).
9. D. LeMignant and R. Goodrich, “NGAO Science Operations Observing Model Trade Study,” Keck Adaptive Optics Note 476 (W. M. Keck Observatory, Kamuela, Hawaii, 2007).
10. V. Velur, A. Bouchez, C. Neyman and D. Gavel, “Rayleigh rejection trade study report” Keck Adaptive Optics Note *submitted* (W. M. Keck Observatory, Kamuela, Hawaii, 2007).
11. V. Velur, “NGAO Laser Guide Star Wavefront Sensor: Type and Number of Sub-apertures Trade Study,” Keck Adaptive Optics Note 465 (W. M. Keck Observatory, Kamuela, Hawaii, 2007).

12. R. Clare, “Keck NGAO Sky Coverage Modeling,” Keck Adaptive Optics Note 470 (W. M. Keck Observatory, Kamuela, Hawaii, 2007).
13. R. Flicker and V. Velur, “NGAO Trade Study Report: LOWFS Architecture,” Keck Adaptive Optics Note 487 (W. M. Keck Observatory, Kamuela, Hawaii, 2007).
14. R. Flicker, “NGAO Trade Study Report: LGS Asterism Geometry and Size,” Keck Adaptive Optics Note 429 (W. M. Keck Observatory, Kamuela, Hawaii, 2007).
15. V. Velur, “Fixed vs. Variable LGS Asterism Cost/benefit Study for NGAO,”Keck Adaptive Optics Note 427 (W. M. Keck Observatory, Kamuela, Hawaii, 2007).
16. A. Moore and S. Adkins, “NGAO Science Instrument Reuse Trade Study Report”, NGAO Twiki website, see: http://www.oir.caltech.edu/twiki_oir/pub/Keck/NGAO/NewKAONs/NGAO_Science_Instrument_Reuse.doc
17. D. Gavel and V. Velur, “NGAO Trade Study: Uplink Compensation”, (W. M. Keck Observatory, Kamuela, Hawaii, 2007).
18. A. Moore and V. Velure, “Interim LOWFS and LGS Object Selection Mechanism conceptual study report”, Keck Adaptive Optics Note 563, (W. M. Keck Observatory, Kamuela, Hawaii, 2007).