NGAO System Architecture Definition

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ABSTRACT

We document the NGAO System Architecture selection process, highlighted by a 5-day System Architecture Retreat held July 9-13, 2007, at which detailed evaluation of five candidate architectures was conducted against a set of predefined architecture evaluation criteria. Preliminary candidate rankings were conditioned by post-retreat analysis of outstanding questions to arrive at a final architecture ranking. The Cascaded Relay architecture is adopted as the NGAO baseline architecture to be carried forward for subsequent design.
## CONTENTS

1. **INTRODUCTION** .................................................. 5

   1.1. **NGAO System Architecture Work Package** .................. 5
   1.2. **NGAO System Architecture Process** ........................ 5

2. **PROCESS ASSUMPTIONS AND INPUTS** .......................... 6

3. **PREVIOUSLY IDENTIFIED CANDIDATE ARCHITECTURES** ............ 6

4. **SYSTEM ARCHITECTURE RETREAT PREPARATION** .................. 7

5. **SYSTEM ARCHITECTURE RETREAT** ................................ 7

   5.1. **Candidate Architecture Breakout Group Charge** ............... 7

6. **SYSTEM ARCHITECTURE 1: THE “SPLIT RELAY”** .................. 8

   6.1. **Revised Working Definition** ................................. 8
   6.2. **Requirements Satisfaction** .................................. 9
       6.2.1. Performance Requirements ............................. 9
       6.2.2. Operational Requirements ............................. 10
   6.3. **Pros and Cons** ............................................ 10
       6.3.1. Pros .................................................... 10
       6.3.2. Cons .................................................... 10

7. **SYSTEM ARCHITECTURE 2: THE “ADAPTIVE SECONDARY MIRROR”** .... 11

   7.1. **Revised Working Definition** ................................ 11
   7.2. **Requirements Satisfaction** ................................ 12
       7.2.1. Performance Requirements ............................ 12
       7.2.2. Operational Requirements ............................ 12
   7.3. **Pros and Cons** ............................................ 12
       7.3.1. Pros .................................................... 12
       7.3.2. Cons .................................................... 12


   8.1. **Revised Working Definition** ................................ 13
   8.2. **Requirements Satisfaction** ................................ 14
       8.2.1. Performance Requirements ............................ 14
       8.2.2. Operational Requirements ............................ 14
8.3. PROS AND CONS 14
  8.3.1. PROS 14
  8.3.2. CONS 15

9. SYSTEM ARCHITECTURE 4: THE “KECK I UPGRADE PATH” 15
  9.1. REVISED WORKING DEFINITION 16
  9.2. REQUIREMENTS SATISFACTION 16
    9.2.1. PERFORMANCE REQUIREMENTS 16
    9.2.2. OPERATIONAL REQUIREMENTS 18
  9.3. PROS AND CONS 18
    9.3.1. PROS 18
    9.3.2. CONS 18

10. SYSTEM ARCHITECTURE 5: THE “CASCADED RELAY” 19
  10.1. DEFINITION 19
  10.2. REQUIREMENTS SATISFACTION 20
    10.2.1. PERFORMANCE REQUIREMENTS 20
    10.2.2. OPERATIONAL REQUIREMENTS 20
  10.3. PROS AND CONS 20
    10.3.1. PROS 20
    10.3.2. CONS 21

11. OTHER ARCHITECTURES 21
  11.1. DNIRI ON A SEPARATE TELESCOPE THAN A NARROW-FIELD AO RELAY 21
  11.2. SIMULTANEOUS NGAO CAPABILITY ON BOTH KECK 1 AND KECK 2 TELESCOPE 21

12. SYSTEM ARCHITECTURE RETREAT EVALUATION PROCESS 21

13. OUTSTANDING QUESTIONS AND RESULTS 24

14. CANDIDATE ARCHITECTURE SURFACE COUNTS 26
  14.1. ASSUMPTIONS 26
  14.2. SKY-TO-NARROW FIELD SCIENCE INSTRUMENT INPUT 27
  14.3. SKY-TO-DNIRI INPUT 27
  14.4. SKY-TO-LGS WFS INPUT 27

15. FINAL RANKING PROCESS AND BASELINE SELECTION 28

APPENDIX 1. NGAO SYSTEM ARCHITECTURE WORK SCOPE PLANNING SHEET 29
1. Introduction

1.1. NGAO System Architecture Work Package

The NGAO System Architecture work package has as its primary goal the development of a baseline NGAO architecture to be further developed during the NGAO System Design (SD) phase. The primary emphasis of the SD phase has until now concentrated on the development of key scientific and technical inputs to guide the baseline selection. These include the NGAO Science Requirements and System Requirements Documents, newly developed residual wavefront error, encircled energy, high-contrast, astrometric and photometric precision, and transmission and background error budgets and best practices, and approximately 40 technical trade studies that were identified as highest priority during the June 2006 proposal development process (the so-called “Indian Wells process”).

We developed a scope statement and schedule for the System Architecture work package (WBS 3.1.3 in the SD phase plan, see Appendix 1), which laid out an approximately 12 week process for the consideration and downselection of various architecture options that would meet the Systems Requirements when implemented in an affordable, prioritized, traceable, and flexible Observatory program.

A key element of the System Architecture definition plan was a week-long retreat bringing together members of the science team and the technical team to iteratively review the several architecture options previously identified, develop new architecture candidates, and prioritize these architecture candidates for further consideration in the System Architecture work package (see the 2006 NGAO proposal for an iterative process chart.) This retreat was held July 9-13, 2007 with two and eight members of the NGAO science and technical teams, respectively, participating in person, with telephone input during the week from four additional science team members. Caltech and WMKO staff were kindly and effectively hosted by University of California, Santa Cruz staff for the duration of this retreat.

This report details the preparation, activities, key issues, deliberations, and results of the NGAO System Architecture team retreat. As described in the system architecture work scope definition, the final prioritization of candidate architectures, including the selection of an architecture baseline, will depend on a) the initial candidate prioritization based upon our retreat deliberations, b) resolution of key technical issues identified during the retreat, c) additional and more accurate cost estimations, and d) external factors, such as feedback from the WMKO, COO, and UCO Directors, the WMKO Advancement office, and additional science community input (via the NGAO Project Scientist.)

Based on the final prioritization, additional engineering design will occur with emphasis, but not exclusivity, on the top-ranked architecture. Assessment of the key risks and the practicality of our retiring these risks within the constraints of time and resources of the NGAO program may lead to a re-ranking of the candidate architectures. Also within the SD phase, we will develop more detailed cost estimates, which similarly may affect the outcome of the SD phase and the architecture presented at the System Design Review.

1.2. NGAO System Architecture Process

The basic description of the System Architecture process can be in summary described as:

- Review Requirements and Constraints from the Science Requirements Document (ScRD) and System Requirements Document (SRD)
- Review Previously Identified Candidate Architectures
- Develop System Functional Breakdown based on SRD¹ and Detailed Observing Scenario Use Cases²
- Define Subsystem Evaluation Criteria³
- Develop Candidate Subsystems

¹ See Appendix 1.
² At the time this task was necessitated, a detailed document containing NGAO observing scenario use cases was not available. As collateral input to the SRD, however, reference was made to several visible-light AO use cases described in Caltech Instrumentation Note #623, “PALM-3000 Observing Scenarios”, A. Bouchez.
³ See Appendix 2.
• Review and Rank Candidate Subsystems Based on Evaluation Criteria
• Define Architecture Evaluation Criteria
  o Propose Candidate Architectures as Different Combinations of High-Ranking Candidate Subsystems
  o Develop Rough Order of Magnitude (ROM) Differential (Parametric) Cost Estimates for the Candidate Architectures
  o Make Initial Candidate Prioritization
• Resolve Outstanding Technical Issues
• Solicit External Input (e.g. from the WMKO Advancement Office)
• Adopt Baseline Architecture and Baseline Program Scope
• Proceed with Design Development of Baseline Architecture

where the open bullets indicate processes occurring during the System Architecture Retreat.

2. Process Assumptions and Inputs
We based this process upon the following version of key input documents:

• NGAO Science Case Requirements Document, Release 1, Version 10, Claire Max, 3/20/07 (KAON 455)
• NGAO System Requirements Document, Version 1.11, Peter Wizinowich, (KAON 456)
• Architecture reqments summary v5.xls (sic), Max and Wizinowich

And these key assumptions:

1. The science cases identified in these documents are representative of the high angular resolution and high sensitivity scientific goals of the entire W. M. Keck Observatory user community.
2. The NGAO instrument priorities identified in the June 2006 NGAO proposal are unchanged (although the above documents supersede certain parameter values for these instruments).
3. The historical record of atmospheric turbulence conditions on the summit ridge of Mauna Kea is indicative of NGAO operating conditions (see KAON’s 303, 415, 471, and 496)

3. Previously Identified Candidate Architectures
As part of the June 2006 NGAO “Indian Wells” Proposal Development, the NGAO team considered a number of approaches to NGAO, to the extent that NGAO Requirements were known at the time. These approaches were generally describable as:

• A Large AO Relay providing for either MCAO or MOAO implementation options (associated with Retreat Architecture #3 Large Relay)
• Use of an Adaptive Secondary Mirror (associated with Retreat Architecture #2 Adaptive Secondary)
• Upgrades to the Keck I System (associated with Retreat Architecture #4 Keck I Upgrades)

Due to the compactness of the Indian Wells process, we adopted the large AO relay as the architecture that could most easily be understood, as it was most similar to AO systems previously implemented by the team, such as the first generation Keck AO systems. However, we noted a significant number of outstanding questions at the time and indicated the importance of addressing these issues during the SD phase in our June 2006 proposal. These questions became the basis for our significant body of trade studies and technical reports written to date.

One of the key trade studies identified at Indian Wells was the tradeoff between multiconjugate (MCAO) and multiobject (MOAO) systems. Don Gavel undertook this study in what became KAON 452, in which he referred to purely MOAO architectures having some heritage with ESO’s Falcon instrument as well as concept development during the initial TMT

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4 See Appendix 2.
5 During the retreat, this document was modified, beginning from v3 of the (otherwise) same filename.
instrument feasibility study phase. From this, supported by the optical relay trade study (WBS 3.1.2.2.2) there emerged another architecture not previously described at Indian Wells:

- An MOAO-based small field of view AO relay (associated with Retreat Architecture #1 Split Relay)

These four architectures were reviewed at the beginning of the WBS 3.1.3 work package as the ‘top-down’ architectures, namely those architectures that were believed to provide plausible technical solutions for meeting NGAO requirements.

4. System Architecture Retreat Preparation

In preparation for the System Architecture Retreat, the architecture team tasked Rich Dekany to develop a set of skeletal architectures corresponding to the four ‘top-down’ architectures. These included basic component choices (typically constrained by DM availability) and design approaches to ground the retreat review of these architectures and to spur creative thinking by the team. The initial form of these architecture summaries took the form of large (3’ x 5’) posters which were hung on walls during retreat breakout sessions and marked up as the breakout teams debated the issues pertaining to each.

During the development of the Adaptive Secondary Mirror architecture option, Rich Dekany identified two branches, namely that wherein the AM2 provides all orders of correction and an alternative in which a subsequent AO stage, having a DM of higher order than AM2, is used in conjunction to provide final correction. Early in the consideration of this later option, however, it became clear that there was little advantage to having a medium-order AM2, as it did not loosen the requirements on downstream DM’s (particularly those in DNIRI). Given the ScRD’s downplay of L- and M-band science (for which a medium-order AM2 would suffice), we elected to not carry this alternative further and instead concentrated on a ‘full-up’ AO correction capability delivered by the AM2 as the basis for our adaptive secondary mirror candidate architecture.

5. System Architecture Retreat

The 7/9-13/07 System Architecture Retreat had as its Objectives:

- Identify & rank candidate architectures
- Develop architecture system-level cost estimation
- Progress on subsystem functional requirements
- Understanding of how the different architectures imply different program structures (for example, a Keck upgrade could offer an incremental approach to development & science return)

This was realized by a review of the candidate architectures, proposition of new architectures, differential cost estimation, and initial ranking of architectures according to our architecture selection criteria, and assignment of action items to address outstanding issues for the next phase of the WBS 3.1.3 process.

5.1. Candidate Architecture Breakout Group Charge

Each of the four top-down architectures was reviewed during the retreat with the following requested as deliverables to be returned to the plenary group (with ~30-40 total workhours allocated to each architecture):

- A revised definition of the architecture design
- A summary of requirements satisfaction
- A list of technical pros and cons
- A ROM cost estimate\(^6\)

In some cases, certain subsystem choices are not specific to particular architectures, and these were generally noted during the architecture compison and subsequent deliberations. The adoption of many subsystem baselines, reflecting our

\(^6\) In practice, differential ROM cost estimates were all later built into a separate cost comparison developed as homework for Don Gavel and Viswa Velur on the evening of 7/11/07. The basis for the cost estimates are detailed in the file “Notes on costing doc”. The details of the cost comparison itself has not been made public to protect Observatory interests with respect to vendor price negotiations.
process candidate subsystem ranking, but in the context of an actual baseline architecture, will be made during the remainder of the SD phase.

Team members: Bauman, Le Mignant, McGrath, Moore, Velur, Wizinowich.

We start with an architecture where the wide field required for the Tip-Tilt star acquisition and DNIRI instrument is siphoned first, allowing a simple refractive design for the narrow field relay to be implemented for the remaining science instruments. A block diagram schematic of this layout is shown in Figure 1.

6.1. Revised working definition
In the figure the Keck tertiary mirror is to the left of the diagram and light is fed from left to right. Assumed for this system, but not shown in the diagram, are a calibration unit and a LGS WFS unit fed first using appropriate optical elements all located in the elevation bearing of the Keck telescope. The light path travels to a beamsplitter exchanger that feeds the wide field DNIRI instrument. This is also the location for the Tip-Tilt pick-off unit, that in this incarnation covers a 180arcmin field. A 20 arcsec field is fed to a simple refractive relay design that includes a removable ADC unit. The relay images the telescope pupil onto a 25mm 64X64 actuator MEMS DM. The output of the relay sends light to the narrow field science instruments and, via a beamsplitter, the NGS WFS unit.

In more detail the layout has the following assumptions:

- **LGS**
  - LGS pick-off is first
  - Pick-off to DNIRI second & requires a dichroic changer (to switch which wavelengths go to dNIRI sensors and which goes to narrow field science instruments)
  - DNIRI provides platform for 2 TT, 1 TTFA, 1 TWFS over 180” dia field for both dNIRI and narrow field science
  - Each DNIRI channel includes a 32X32 MEMS DM
- **NGS**
  - NGS WFS fed by narrow field relay (and can therefore be closed loop).
  - There is no NGS with dNIRI
  - The laser dichroic is removed for NGS WFS
- **Acquisition, Dither, & Tracking**
  - There is a 64x64 MEMS included in each TT pick-off
  - Need ADC for narrow field science instruments (but not for dNIRI science units)
  - Need ADCs for tip/tilt sensors (in order to sense across J & H simultaneously)
  - Need TT, TTFA sensors to either allow offset tracking for differential atmospheric refraction or to track the unit, or this could potentially be addressed by having ADCs in both LOWFS and science paths.
  - Differential tracking required for non-science sensors on dNIRI platform to allow for a non-sidereal science object on narrow field science instruments
  - Acquisition camera in front of narrow field relay
- **Calibration**
  - PSF provided by 1 of DNIRI science channels
  - Need an accurate registration system between acquisition camera and all NGS & science sensors
  - Would be good to have 1 TT sensor close to science instrument (e.g., on IR science camera)

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Subsequent analysis concluded that the LGS WFS package would be very difficult to mount inside the elevation bearing of the telescope. The LGS WFS pickoff was therefore moved back in the optical train, to follow the DNIRI pickoff (but before the narrow-field relay collimator) as shown in Figure 1.
Figure 1. A schematic layout of the Split Relay architecture. [In this and subsequent schematic layouts color coding is used to represent different features. Optics/subsystems shown in green rotate, MEMS DM’s are magenta in color while piezo DMs are blue colored. DNIRI/ TT pick off and path are shown in red and yellow coloration is used for the LGS WFS pick off, path and enclosure.]

6.2. Requirements satisfaction

6.2.1. Performance Requirements

It was felt in general that the delivered image quality and encircled energy requirements could be met with this layout assuming open loop/tomography to be viable at the levels described in KAON 471, where there typically is allocated 30-50 nm rms wavefront error from all sources pertaining to open loop (e.g. go-to) control such as wavefront sensor nonlinearity and deformable mirror nonlinearity. (At the same time, the error budgets of KAON 471 recognize the reduction in wavefront error arising from greatly reduced anisoplanatism and generalized anisolantism terms in this architecture.)

Visible Imager & Spectroscopy
- Because of drift, which is difficult to monitor, it would be hard to acquire target on a 14mas slit.
- Using calibration source, need to register camera optics within 1 micron precision (pixel size is 5microns)
6.2.2. **Operational Requirements**

**All narrow field instruments**
- PSF estimation—how do we achieve this given different wavelength, pixel scale, open loop
- There is a lot of non-common path for LGS between DNIRI platform and narrow field science instruments (separate rotators, separate DMs, separate TTM, non-common ADC). This impacts relative TT and relative WFE and PSF calibration (and note that this varies in time).

**More calibration effort will be required due to:**
- Open loop LGS sensors
- Open loop TT sensors
- Registration of acquisition camera to NGS & science sensors

**Acquisition camera**
- If location of the acquisition camera is on the beamsplitter exchanger then one can’t monitor dNIRI at the same time—any drift would be hard to monitor
- If instead a fold mirror feeds an acquisition cameras behind the exchanger, one needs to remove it when using the narrow field, but this does provide parallel observations with dNIRI
- An (extra?) acquisition camera in parallel with narrow field instruments could be used as a PSF monitor

6.3. **Pros and cons**

6.3.1. **Pros**

**Compact size**
- The Split Relay has a very small footprint, freeing up space for other operational tasks on the Nasmyth platform. Because the architecture is so compact, however, there are other concerns regarding interference with the El bearing and packaging of instruments on the Nasmyth platform (see cons below). Additional back focal distance from the El bearing can be obtained by either pushing back the Nasmyth focus (and accepting the resultant spherical and other aberrations), or by development of a new (passive) secondary (see discussion of new secondaries under the AM2 Architecture.)

**High transmission / Low background**
- Because this architecture employs no common AO optical relay, there are relatively few optical surfaces between the telescope and science instrument input. This maximizes the potential optical transmission for both science bands and laser wavelengths.
- Similarly, the small number of optical surface implies that our emissivity requirements can be met with relatively modest cooling of the narrow field relay. In the case of DNIRI, where there may be as few a 3 telescope + 3 AO system surfaces before DNIRI input, and no moving K-mirror, it may be possible to operate at ambient temperature while meeting the background requirements.

6.3.2. **Cons**

**Space constraints**
- Unclear that dNIRI can fit close enough to El journal
- Unclear if there is enough space for dNIRI & narrow field at same time

**Interferometer**
- Refractive relay won’t pass all the way from J to N-band for interferometer
- Narrow field relay won’t pass large enough field to interferometer

**Calibration**
- In this architecture there is some concern over the non-common path accuracy between the TT location and narrow field science instruments. This is particularly true due to the adoption of rotators over a single k-mirror field de-rotator.
Team members: Dekany, Gavel, Neyman, Max.

As the name suggests this architecture centers on the presence of a deformable secondary mirror in the system feeding directly the NGAO instruments. There is no relay in this architecture, although there are optics in the light path, namely those required to split off sodium LGS light and to split off NGS stars into a LOWFS package, typically using a fraction of J+H band light.

![Figure 2. A schematic layout for the Adaptive Secondary architecture](image)

7.1. Revised working definition
The AM2 breakout group immediately considered the development of an AM2 with equivalent wavefront fitting error to the N=64 across piezostack mirrors a very high risk and probably cost driver. The decision was made to simplify the concept design down to an AM2 having N = 18 rings (N = 37 actuators across), similar to the format of the VLT adaptive secondaries. The consequence of this is to either 1) tighten the error budget allocation for several other non-fitting error terms, the cost impact of which is currently unknown, or 2) assume a 2nd stage N=64 across DM correction for the narrow-field NGAO instruments. The later of these options seemed self-defeating, as in this case AM2 was unnecessary and we would simply prefer the Split Relay architecture without the sizable price of the AM2.

The breakout group considered the space constraints of this architecture sufficiently difficult that it sought approaches to increase the back focal distance from the telescope E1 bearing. There was general sentiment that since a new M2 is by definition to be fabricated in this architecture, it might as well be one that provides additional BFD. Rich Dekany quickly calculated that an F15.4 Ritchey-Christien design could provide an additional 1.5 m of BFD, which in turn would allow DNIRI, for example, to be fed with an additional fold and enjoy a gravity-invariant orientation on a barrel rotators on the Nasmyth platform. (The ability of the primary mirror to approximate the new M1 conic constant in this design was not evaluated, but must be to validate this as an issue mitigation.)
7.2. Requirements satisfaction

7.2.1. Performance Requirements

It appeared difficult to meet the wavefront error budget performance goals with this architecture, without tightening other terms in the error budget. The cost of this was unknown but because this architecture was already seen to suffer significantly in cost disadvantage compared to the others, we did not pursue the ‘WFE budget tightening’ cost increment further.

7.2.2. Operational Requirements

While some NGAO operational requirements, such as rapid instrument switching, could in theory be satisfied, given sufficient back focal distance from the elevation bearing, the overall impact of an AM2 on telescope operations was not clear to us. Although it may sound trite, we were of the opinion that as long as such an AM2 work perfectly, it would be operationally straightforward, but that any non-routine service would be a major encumbrance on the Observatory.

7.3. Pros and cons

7.3.1. Pros

- Provides excellent transmission to directly-fed instruments (even more so for Cass focus)
- Minimizes background for directly-fed instruments (even more so for Cass focus)
- Provides excellent polarimetry for directly-fed instruments (not clear whether modern polarimeters prefer Cass for Nasmyth)
- May provide a convenience mirror for precision MCAO implementation in combination with a narrow-field precision AO relay
- Provides a facility upgrade that may be exploited in future to-be-defined ways (e.g. GLAO imager, L/M band imager)
- Laser guide star beams 'enjoy' AM2 correction. This may ease the optical requirements on the HOWFS's and potential mitigate some 2nd order wavefront error effects (e.g. those that scale with the absolute value of image motion)
- New AM2 allows us to push back the tertiary-to-focus distance, providing more room on the Nasmyth platform for instruments (esp. DNIRI)
- + the other benefits described in KAON 485

7.3.2. Cons

- Large cost and cost risk
- Potential disruption to operations and loss of observing time
- Failure to achieve full modal correction could compromise performance (might be mitigated in an precision MCAO implementation)
- Actual tip/tilt performance of the AM2 is unknown
- There is some debate as to the practical advantage of this - suggest detailed simulations to capture 2nd order effects
- + the other issues described in KAON 485

8. System Architecture 3: The “Large Relay”

Team members: Dekany, McGrath, Moore, Neyman, Velur.

This architecture puts DNIRI behind the relay, which passes the entire 180” field. It was designed to accommodate MCAO mode in order to mitigate the risk of open loop MEMs DMs. It could be upgraded to an MOAO system in the future, or changed to an MOAO architecture prior to the design phase if MEMs are proven to meet the performance needs. A schematic of the entire system is shown in Figure 3. A close-up of the narrow-field instrument “LEGO block” configuration is shown in Figure 10.
8.1. Revised working definition

In Figure 3 light is fed from left to right through a K-mirror before being passed to any of the instruments, allowing all instruments to remain stationary. The light path travels to a 589 nm dichroic, which splits off the Na laser light and sends it to the LGS WFS. The light then continues on to a dichroic changer, which splits off light to DNIRI (not shown) before continuing on the narrow-field instrument block (Figure 10). A 20” beamsplitter directs light to the narrow-field
instruments, while passing the full 180” field to the LOWFS pickoff. There is the possibility of having all instruments located in a single location, fed by a flip mirror.

In more detail the layout has the following assumptions:

- **LGS**
  - LGS pick-off is first
  - Pick-off to DNIRI second & requires a dichroic changer
  - LOWFS are part of the instrument “LEGO block”, providing the least non-common-path between TT stars and the science fields.

- **NGS**
  - NGS WFS fed by LEGO block
  - The laser dichroic is removed for NGS WFS

- **Acquisition, Dither, & Tracking**
  - There is a 64x64 DM
  - Acquisition camera location?

- **Calibration**
  - PSF monitor on LOWFS?
  - Fast TT at fold mirror with an additional TT mirror for the NIR imager.

**8.2. Requirements satisfaction**

**8.2.1. Performance Requirements**

As identified during the Indian Wells process, the Large Relay architecture appears capable of meeting all of the NGAO performance requirements. Although there remain some detailed issues regarding the optimal packaging of instruments at the output of the relay (in part because all five NGAO instruments would share the same output beam), the packaging issues are probably manageable, given the long back focal distances from the Large Relay OAP #2 (typically 4.5 meters for a 300 mm diameter relay pupil).

**8.2.2. Operational Requirements**

Meeting the background requirements with Large Relay would require cooling a large volume containing an appreciable thermal mass. This would likely complicate NGAO I&T and NGAO routine maintenance considerably (although the practical cost of a ‘meat locker’-type instrument enclosure would not be the cost driver.

**8.3. Pros and cons**

**8.3.1. Pros**

1. Closed loop
   - Lasers, LOWFS, etc., all behind 1 and possibly 2 DMs.
2. MCAO architecture
   - Can adopt MCAO architecture now and then change to MOAO with MEMS when proven, with minimal issues.
3. Large contiguous field
   - Since the entire 180” field is being passed through the relay, there is a possibility of upgrading to a wide-field imager, with some correction over the entire field, in the future.
4. Common PSF available over 120”
5. Potentially suitable for Interferometer
8.3.2. **Cons**

1. Large instrument that needs to be cooled
   - May only need 2 DAZLE size meat lockers.
2. Unclear if the instrument will fit on the platform
   - Also may be a problem for observatory maintenance because there is no clear access to the bearing. Need advice from Observatory for this.
3. MCAO option only provides 60” field fully corrected (50% EE)
   - Performance drops (to 30%?) at 120”
   - May need MEMs in outer field to correct TT stars
4. MCAO requires 2 DMs, one at ground and one at 5km
   - One is 225mm (64 actuators, 3.5mm pitch) and the other is 330mm (64 actuators, 5mm pitch).
   - This comes with a higher cost

9. **System Architecture 4: The “Keck I Upgrade Path”**

Team members: Bauman, Gavel, Max, Wizinowich.

This architecture considers an upgrade to the current Keck I AO system to achieve the performance requirements of NGAO. Many of the issues were presented in KAON 462 and 461. In this scenario NGAO is a program, producing science along the way, and is not just a final delivered system.
Figure 4. A schematic layout of the Keck 1 Upgrade Path architecture. The magenta rectangle represents a small diameter MEMS DM (mounted on a tip/tilt stage) embedded in a new 2nd OAP relay that follows an upgraded form of the existing Keck 1 AO system. The NGS WFS is not shown on this figure, but could be flipped into the beam after the ADC, similar to prior architectures considered.

9.1. Revised working definition
As a fundamentally different architecture than the others this upgrade path has no official working definition. Peter Wizinowich considered a plausible upgrade path, as a series of Keck 1 Upgrades, in KAON 461, and Rich Dekany revisited the question of ‘bang for the buck’ using the NGAO wavefront error budget tool, which has been updated since the writing of KAON’s 461/462. It was assigned as an action item from the System Architecture Retreat for Peter Wizinowich to propose a specific upgrade plan, with well defined installation periods (and subsequent early science return)⁸.

9.2. Requirements satisfaction

9.2.1. Performance Requirements
It appears that we can meet nearly all of the NGAO performance objectives via upgrades to the Keck 1 AO system. The practical difficulty of handling an aging system, performing many complex upgrades at the Mauna Kea summit, and disruptions to AO operations are offset by early science return.

⁸ These actions were completed and are documentation in KAON’s 500 and 502.
The effect of pupil wander is not yet evaluated. The telescope pupil will move around on the DM because of the existing tip/tilt mirror not being at a pupil. This pupil illumination may be too much. We could mount the DM on a low bandwidth tip/tilt stage and have the tip/tilt mirror offload to it, however.

Other performance issues:

Field of regard
- Current system passes > 2’. Likely does not pass 3’. This effects sky coverage\(^9\).
- Should look at whether mods could be made to things (like the Wyko fold mirror) that vignette the beam.
- Would be good to figure out the actual field and vignetting sources.
- If dNIRI is up front then it could provide the LOWFS (over the entire field or just over an annular field) and the 2’ field to the rest of the system would be more than adequate.
- The existing AO system doesn’t have an IR acquisition camera for tip/tilt and even if it did it wouldn’t cover the 3’ field. This implies that you need an IR acquisition (or visible) before the AO system (possibly in El ring).

Companion sensitivity
- K-mirror allows you to keep telescope pupil and AO orientation, and hence speckles, fixed (i.e., ADI).
- Science instrument on a rotator is not as good for companion sensitivity.
- Mirrors near a focus are bad, especially ones that move. Could improve by getting flatter mirrors and/or moving them further from focus.

Astrometry
- May need to implement IR ADC.

PSF estimation
- There are options to have a patrol field camera (could be at same location as LOWFS on AO bench)

LGS sensors
- Could potentially fit into the existing WFS location.
  - Advantages: Closed loop. Less likely to need MEMS in LGS WFS. Image rotation provided. Fixed gravity vector.
  - Disadvantages: Significant space constraints.
- A fixed asterism would make this easier, but it might still be feasible with a variable geometry. We can’t use just a fixed asterism if this also has to serve dNIRI or if want to sharpen LOWFS.
- Could also locate the LGS sensors in the elevation journal as proposed for other architecture options. This requires open loop correction.

LOWFS location
- Could be located at kinematic plate location fed by a changeable dichroic (at the Interferometer Science Fold Mirror location). Depends on how large the IR dewar needs to be.
- Existence of at least a woofer DM (current DM) is that 32x32 MEMs for LOWFS is certainly adequate.

Instrument Switching
- Could have two NIR instruments and one small visible instrument available simultaneously.
  - NIR instruments
    - One NIR science instrument could go at the NIRC2 location and another at the OSIRIS location.
  - Visible instruments
    - Can remove existing tip/tilt and LBWFS sensor stage. Might be sufficient room at this location for a visible imager.

---

\(^9\) The magnitude of this degradation was subsequently quantified in KAON 504.
To have a visible instrument available at one of the existing instrument ports would require having a dichroic changer (to allow the visible light through the currently IR transmissive dichroic). Alternately, could take collimated light to an instrument at the changeable port the same way the Interferometer takes light (fold between DM and 2nd OAP).

9.2.2. Operational Requirements
There was some debate and questions were raised regarding the ability of this architecture to fulfill the reliability and maintainability requirements for NGAO. The aging of the system (with many components becoming 20 years old in 2015) raises issues of both fault likelihood and obsolescence.

9.3. Pros and cons

9.3.1. Pros
Science implementation
- Even if this upgrade architecture doesn’t ultimately get us to NGAO it still may be a viable incremental strategy to get to NGAO. Could implement and demonstrate, and use for science, many of the critical elements of NGAO along the way.
- Science along the way (could also be a parallel effort to an NGAO instrument).
- New capabilities as funding available.
  - But even if all funding available might still chose a program where upgrades were part of the program.

9.3.2. Cons

Backgrounds high due to lots of optics
- Number of ways to improve this noted in KAON 462
- AO enclosure is a meat locker so it is insulated enough to permit cooling.
- Would need to add a window.
- Could alternately cool only the bench but this would then require windows to the science instruments as well.
- Some of the existing AO components may not do well when cooled and might need to be replaced.

Science Instruments
- DNIRI
  - DNIRI loses its advantage if it is put behind all of the existing AO bench optics unless these optics are cooled. However, these optics were not designed to be cooled and there may be various mechanical problems as a result.
  - Putting DNIRI at the front of the AO bench, while leaving the bench in place, would be a significant challenge. In addition to a tight fit with the elevation journal would have to deal with a tight fit with all of the AO opto-mechanics at the front of the AO bench, especially the rotator. DNIRI would need to be suspended above the bench and the bench cover and snout of the AO enclosure would need to be significantly modified.
  - Another option is to move the AO bench out when using DNIRI,
    - This implies have to have LGS WFS in El journal.
    - Have to have separate LOWFS for DNIRI.
    - Limited to only AO bench field for LOWFS.
    - Have to make AO bench movable.

Other
- Some of the hardware will be obsolete by the time of NGAO
- All agreed that a better system could be built from scratch rather than upgrading a well performing but non-optimum system
- Scheduling and timetable need careful consideration for this option
- DM upgrade
  - A 64x64 DM the same size as the existing DM would likely be expensive.
Could relatively easily upgrade to a 40x40 DM with 3.5 mm pitch (and perhaps this is adequate for NGAO?).
An alternative to replacing existing DM would be to put a second higher order DM (a 64x64 MEMS or photonics module DM) in the science instrument or path to science instruments.

10. **System Architecture 5: The “Cascaded Relay”**
Team members: Bauman, Dekany, Gavel, Le Migrant, Max, McGrath, Moore, Velur, Wizinowich.

This architecture uses a modest-size, low-order 1st optical relay to provide partial compensation for the LGS HOWFS, the NGS LOWFS, and DNIRI, in combination with a small, high-order 2nd optical relay to provide precision wavefront control for the narrow-field science instruments.

10.1. **Definition**
A number of iterations of a cascaded relay that provided partial closed-loop operation of the LGS WFS’s was knocked around during a two-hour brainstorming session of the entire team on 7/10/07. The resultant concept became know as the Cascaded Relay and was assigned Retreat Architecture #5. Cascaded Relay mitigates the major risks of Split Relay, without the massive physical infrastructure of Large Relay, while suffering worse transmission losses due to increased science path surface counts (background, however, is not compromised as all optics in the architecture are enclosed in a cooled enclosure.)

![Figure 5. A schematic layout for the Cascaded Relay architecture. The NGS WFS (not shown) would sample the light downstream of OAP4, but before the back-end instrument stack, with an NGS patrol field of 30” circular diameter.](image-url)
The major features:

- Field rotation is taken out for all subsystems using an upfront (but cooled) K-mirror derotator
- DNIRI is fed with a single wide-field optical relay, while the narrow FoV instruments are fed by this same relay, followed by a second 'precision, narrow field’ relay
  - The first relay
    - Passes an unvignetted 120 arcsec FoV\textsuperscript{10}
    - Has ~100 mm pupil size at which is located a DM having order of N=20 actuators across, conjugated to the ground.
  - The second relay
    - Passes an unvignetted 30 arcsec FoV
    - Has ~25 mm pupil size at which is located a DM having order of N=64 actuators across, conjugated to the ground.
- A full field 589 nm dichroic pickoff sends light the to LGS WFS unit after the first relay, but before the second relay
- A facility LOWFS is integrated into DNIRI
  - The LOWFS package resides at intermediate focal plane (e.g. between the two relay stages)
- Narrow field instruments could be stacked in the “LEGO unit” described for Large Relay (fold mirror chooses instrument, all instruments mounted to same structure).

10.2. Requirements satisfaction

10.2.1. Performance Requirements

Cascaded Relay appears capable of meeting all of the NGAO performance requirements at modest technical risk, with a optical design that eases sensor and instrument packaging constraints (moving away from the telescope elevation bearing), at the cost of additional transmission losses due to increased surface counts.

10.2.2. Operational Requirements

Cascaded Relay appears capable of meeting all NGAO operational requirements in a volume that is intermediate between Large Relay and Split Relay. With a first relay pupil size ~ 30% smaller than the current Keck AO system, it will have an areal footprint approximately 50% smaller, easing the tasks of cooling, AO system maintenance, and other activities occurring on the Nasmyth platform.

10.3. Pros and cons

10.3.1. Pros

- The presence of the relay means that DNIRI is away from the elevation bearing
- DNIRI, LGS and LOWFS receive a global low order correction
- Instruments are non-rotating
- DNIRI is reasonably unconstrained in packaging, and is easier to add later
- The main relay is smaller than large relay architecture, easier to cool, maintain etc
- In event of MEMS mirror failure (lifetime for example) there is a fallback mode
- K-mirror is smaller if away from focus
- The first relay could be implemented with a 5 mm pitch DM, possibly now a stock item at some vendors
- Anna likes this layout <grin>
- Can potentially feed interferometer more easily than other architectures
- Can be extended to MCAO with third stage (after 30 arcsec relay)\textsuperscript{11}
- May have space to add another wide field instrument at DNIRI location

\textsuperscript{10} Subsequent analysis (KAON 504) has led to an unvignetted technical FoV for LOWFS patrol of 180 arcsec diameter. 
\textsuperscript{11} Subsequently, a feasible optical package containing both 0 km and 10 km conjugate DM’s in the initial (wide-field) relay was developed by B. Bauman (documented in an upcoming KAON).
• HOWFS has no MEMS DM’s, which was at times discussed as options of both Cascaded Relay and Split Relay in order to reduce the required linear dynamic range of the HOWFS, since it sees low spatial frequency in closed loop
• PSF calibration possible but further thought re. required field for science instruments (again a comment for other architectures). TOP LEVEL QUESTION-what is the required field for PSF calibration?\(^\text{12}\)
• There are some solutions for acquisition, but needs further thought (a comment for all architectures, really)

10.3.2. Cons
• Lower transmission for both the LGS path (loss of laser return) and instruments path (reduced sensitivity, but potentially offset by higher Strehl with less risky architectural approach)
• LOWFS away from science instruments, though all are not rotating
• Extra complication of Woofer-tweeter control required
• Potentially more scintillation, static aberrations etc due to large number of surfaces- needs to be controlled
• Packaging may be constrained if this feeds interferometer?

11. Other architectures
The following alternative architecture were discussed during the July 9-13, 2007 System Architecture Retreat, but were not fully developed for the reason(s) described below:

11.1. DNIRI on a separate telescope than a Narrow-Field AO relay
Although it appeared potentially feasible to share laser light between AO systems using long photonic crystal fibers (with additional losses in the 20-30% range), we concluded that the duplication of LGS wavefront sensor and low-order NGS wavefront sensor subsystems could not be cost justified. As a datum, we quickly estimated the duplication of a 9-LGS asterism Shack-Hartmann sensor on a second telescope would cost on the order of $3-4M, and duplication of an infrared LOWFS system having 2 TT sensors and 1 TTFA sensor (and associated acquisition systems) to be similarly in the $3-4M range. Because DNIRI has lower requirements for high-order wavefront correction, reuse of the Keck 1 Na laser being developed by LMCT seemed an interesting solution to simultaneous twin-Keck operations, but the necessary sensor systems appeared prohibitive.

11.2. Simultaneous NGAO capability on both Keck 1 and Keck 2 Telescope
Although it appeared to point in the direction of the long-term strategic vision of the Observatory, we did not seriously consider as part of this process the duplication of the full laser power necessary to enable 170 nm rms wavefront error on both Keck telescopes simultaneously.

Without purchasing additional laser power, it is possible to consider duplicating the NGAO science path optical train on the other Keck telescope, and perhaps maintaining current single-LGS performance thereon, strictly for the purpose of supporting dual telescope operation of Keck Interferometer.

12. System Architecture Retreat Evaluation Process
Upon completion of the various breakout group and brainstorming sessions, Peter Wizinowich prepared a top-level summary comparison of the various architectures, shown in Figure 6. Peter provided an excellent summary of the major differences between architectures while the entire team recorded their own questions, concerns, and notes. During this approximately 30 minute summary, Peter was allowed to proceed nearly uninterrupted, resulting in a clear and unbiased overview of the key architectural content, advantages, and disadvantages. Following this, Rich went around the entire room (and video connection to WMKO) asking each team member to comment on the top-priority concern or question from Peter’s summary. A few clarifications were made and Peter updated the summary table accordingly.

\(^{12}\) Currently, this remains an open question, but we note that near the galactic pole, within a 30” circular FoV, there is very likely to be an mV $= 20.5$ star, and perhaps an mV $= 20$ star, that can be used as a PSF reference (at some cadence which depends on the final point source sensitivity of whichever science or PSF reference camera is used.)
During Don Gavel’s period of questioning, there was both clarification and revision of the initial cost differentials in Peter’s summary. As the author of the cost comparison, it became clear that in the first pass, the cost comparison was not strictly “apples to apples”. With Don’s help, over about a 30-40 minute period, we resolved the largest cost estimate discrepancies and arrived at differentials that satisfied us to within an approximate $5M uncertainty. In other words, architectures having less than $5M cost differential were deemed ‘equivalent’ to within our understanding of cost basis (admittedly ROM only).

Following this, Rich Dekany suggested that a constructive way forward, allowing each of the team members a chance to raise and have addressed their top concerns was to pose the question, “What would you need to see to make Architecture X top-ranked?” This generated a list of action items (see Section 13) for post-retreat consideration and allowed the preliminary ranking process to move forward while establishing a process for subsequent ranking revision, if necessary.

At this point, the relative (technical) rankings of the Adaptive Secondary and Large Relay were by consensus lower than the other three architectures, with Adaptive Secondary clearly lowest priority due to its large technical risk. The Cascaded Relay emerged as surprisingly devoid of drawbacks and was given the top technical ranking based on the potential for excellent performance at low risk (albeit at lower transmission.)

Considerable discussion of the relative ranking of the Split Relay and Keck I Upgrade approach followed. At length, it was clear that these were very different approaches with quite different advantages and disadvantages. There was general agreement that Split Relay would provide the best ultimate performance (best transmission, lowest wavefront error) if the technical risk areas of MOAO ‘go-to’ control and mechanical packaging around the elevation bearing could be addressed. Although the VILLAGES experiment is expected to demonstrate control of several risk items in the Split Relay architecture, this input would not be available in the time scale of our WBS 3.1.3 process. For this reason, Split Relay was tentatively given technical rank 3, below Keck 1 Upgrade at rank 2.

As part of these complex discussions, we proceed to document our collective evaluation of each architecture against the previously established architecture selection criteria. These evaluations are included in Table 6.

Following this session, the NGAO EC (Dekany, Gavel, Wizinowich) along with Project Scientist Max and assistant McGrath met in closed session to discuss programmatic discriminators among architectures. What emerged were the programmatic criteria in Appendix 2, along with our evaluation of each architecture against these criteria. The EC was primarily concerned with understanding how different architectural paths delivered early (or late) science return to the community, how different architecture elements might be phased with respect to each other, and specifically what the implications to on-going science operations for the Keck 1 upgrade might be.

The result was a second evaluation ranking in which Split relay emerged as highest ranked (though only slightly), in part because it was considered an architecture that could accelerate either DNIRI or the narrow-field instruments (while all other architectures typically relied on the narrow-field AO capability to be in place prior to DNIRI). Otherwise, Cascaded Relay was equivalently ranked, but this factor brought it to programmatic ranking 2. Keck I Upgrade suffered from the potential complexity and impact on Observatory staff, so was programmatically ranked 3, yet still ahead of Large Relay rank 4 and Adaptive Secondary rank 5, both of which suffered as being “all or nothing” architectures that were inflexible to funding uncertainties and that required the largest up-front investment before science benefits accrued.

Finally, a preliminary joint ranking was made, with Cascaded Relay rank 1, Split Relay rank 2 (moving ahead of Keck 1 Upgrade based on programmatic advantages), Keck I Upgrade rank 3, Large Relay rank 4, and Adaptive Secondary rank 5.
### NGao Systems Architecture

#### Architecture #

<table>
<thead>
<tr>
<th>Name</th>
<th>Split Relay</th>
<th>Adaptive Secondary</th>
<th>Large Relay</th>
<th>Keck I Upgrade</th>
<th>Exaggerated Relay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>dNIRI at focus + 30” delay relay</td>
<td>ASM feeds all instruments</td>
<td>Large relay for all instruments</td>
<td>Upgrade with 110% LOS AO system</td>
<td>Large relay + 30” relay for non-dNIRI instruments</td>
</tr>
<tr>
<td>Overall Ranking</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Technical Ranking</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Programmatic Ranking</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Nasmyth AO size</td>
<td>Medium (current AO bench)</td>
<td>Medium (current AO bench)</td>
<td>Medium (current AO bench)</td>
<td>Medium (current AO bench)</td>
<td>Medium (current AO bench)</td>
</tr>
<tr>
<td>Rotation</td>
<td>dNIRI mirror, K-mirror in relay</td>
<td>Instrument mirror, K-mirror</td>
<td>K-mirror</td>
<td>K-mirror</td>
<td>K-mirror</td>
</tr>
<tr>
<td>LOWFS locn</td>
<td>On or near dNIRI</td>
<td>On or near dNIRI</td>
<td>After relay</td>
<td>After relay</td>
<td>After 1st relay</td>
</tr>
<tr>
<td>NIRM locn</td>
<td>Upgrade at 1st focus</td>
<td>Upgrade at 1st focus</td>
<td>AO focus</td>
<td>AO focus</td>
<td>AO focus</td>
</tr>
<tr>
<td>Nirm in use</td>
<td>After relay</td>
<td>After relay</td>
<td>After relay</td>
<td>After relay</td>
<td>After 2nd relay</td>
</tr>
<tr>
<td>Iris in use</td>
<td>After relay</td>
<td>After relay</td>
<td>After relay</td>
<td>After relay</td>
<td>After 2nd relay</td>
</tr>
<tr>
<td>Interferometer</td>
<td>Doesn’t meet needs</td>
<td>Doesn’t meet needs</td>
<td>Already works</td>
<td>Already works</td>
<td>Already works</td>
</tr>
<tr>
<td>DM</td>
<td>64x64 MEMS for narrow field in K-mirror</td>
<td>35 act across 11 rings on ASM</td>
<td>64x64 on 2DM</td>
<td>20x20 P2T DM in 1st relay + 64x64 MEMS in narrow field science path</td>
<td>20x20 P2T DM in 1st relay + 64x64 in narrow field science relay</td>
</tr>
<tr>
<td>LWSF locn</td>
<td>18” achievable</td>
<td>180” achievable</td>
<td>180” achievable</td>
<td>120” now, 180” possible with annular mirror</td>
<td>180” achievable</td>
</tr>
<tr>
<td>TTM locn</td>
<td>with DM</td>
<td>ASM</td>
<td>6 km conjugate?</td>
<td>Before relay</td>
<td>In 1st relay</td>
</tr>
<tr>
<td>1st control</td>
<td>Open loop</td>
<td>Closed loop</td>
<td>Closed loop</td>
<td>Closed loop</td>
<td>Closed loop</td>
</tr>
<tr>
<td>HOWFS control</td>
<td>Open loop</td>
<td>Closed loop</td>
<td>Closed loop</td>
<td>Closed loop</td>
<td>Closed loop</td>
</tr>
<tr>
<td>LOWFS calibrations</td>
<td>Most non-common control between LOWFS &amp; non-dNIRI instruments</td>
<td>Least common path control</td>
<td>Least non-common path control</td>
<td>Least non-common path control</td>
<td>Least non-common path control</td>
</tr>
<tr>
<td># of AO surfaces to NIRM instrum</td>
<td>12</td>
<td>4</td>
<td>9-10</td>
<td>9-10</td>
<td>13</td>
</tr>
<tr>
<td>Achieving background</td>
<td>dNIRI at focus, AO relay cooled to ~14C</td>
<td>At tel focus</td>
<td>Cooled to ~10C</td>
<td>Cooled to ~10C</td>
<td>Cooled to ~15C</td>
</tr>
<tr>
<td>NIR PSF estm</td>
<td>Common PSF within 30” only</td>
<td>Big field available</td>
<td>120” field available</td>
<td>120” field available</td>
<td>Partially common-path PSF thru big relay; fully common path within 30” only</td>
</tr>
<tr>
<td>Narrow field performance</td>
<td>Astrometry</td>
<td>High contrast</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High contrast</td>
<td>DHFNS near focus disadvantage</td>
<td>DHFNS near focus disadvantage</td>
<td>K-mirror advantage; K-mirror near focus disadvantage</td>
<td>K-mirror advantage</td>
<td>K-mirror advantage</td>
</tr>
<tr>
<td>&amp; Op's Costs</td>
<td>$0.5M</td>
<td>$0.5M</td>
<td>$0.5M</td>
<td>$0.5M</td>
<td>$0.5M</td>
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<tr>
<td>Goals for K</td>
<td>$8.5M</td>
<td>$8.5M</td>
<td>$8.5M</td>
<td>$8.5M</td>
<td>$8.5M</td>
</tr>
<tr>
<td>Risks</td>
<td>Tight fit to journal; all open loop</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AddF pers</td>
<td>Can benefit other instruments</td>
<td>MCAO option</td>
<td>Early science return</td>
<td>Design &amp; implementation feasibility</td>
<td>Graceful fallback</td>
</tr>
<tr>
<td>AddF costs</td>
<td>Keeping top surface clean</td>
<td>Keeping top surface clean</td>
<td>Full tab design more difficult</td>
<td>Many existing constraints</td>
<td></td>
</tr>
<tr>
<td>Technical Ranking Criteria:</td>
<td>Performance Margin</td>
<td>Good</td>
<td>Fair</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Operations Cost</td>
<td>Good</td>
<td>Fair</td>
<td>Fair</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Cost Risk</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Technical Risk</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Reliability</td>
<td>Good</td>
<td>Fair</td>
<td>Good</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Interface</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>System Expandability</td>
<td>Good</td>
<td>Good</td>
<td>Fair</td>
<td>Poor</td>
<td>Good</td>
</tr>
<tr>
<td>Phasing compatibility</td>
<td>Good</td>
<td>Poor</td>
<td>Poor</td>
<td>Very Good</td>
<td>Fair</td>
</tr>
<tr>
<td>Schedule Risk</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Programmatic Ranking Criteria:</td>
<td>Match to Strategic Goals</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Early Science/Phasing Flexibility</td>
<td>Good</td>
<td>Poor</td>
<td>Fair</td>
<td>Very Good</td>
<td>Good</td>
</tr>
<tr>
<td>Facilitation of Pre-Telescope I&amp;T</td>
<td>Good</td>
<td>Poor</td>
<td>Fair</td>
<td>Poor-Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Implementation Impact on AO Ops during development</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Development Feas to Observing Schedule</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>dNIRI only AO costs</td>
<td>Good</td>
<td>Poor</td>
<td>Poor</td>
<td>Fair-Good</td>
<td>Fair</td>
</tr>
<tr>
<td>Community experience</td>
<td>Poor</td>
<td>Poor</td>
<td>Fair-Good</td>
<td>Fair-Good</td>
<td>Fair-Good</td>
</tr>
</tbody>
</table>

Figure 6. Architecture Comparison Summary, as finalized on July 13, 2007. Subsequent investigations relevant to these results are described in Sections 13 and 15.
### 13. Outstanding Questions and Results

Following this preliminary ranking, Rich Dekany asked all of the team present what information, not currently available, might significantly affect the evaluation rankings over the next several weeks. The list of major questions, organized by architecture, along with the subsequent result (as reviewed during the system architecture team meeting held on 8/23/07), is shown in

<table>
<thead>
<tr>
<th>Candidate Architecture</th>
<th>Question / Issue</th>
<th>Subsequent Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>Need accurate surface counts to evaluate transmission and emissivity challenges</td>
<td>V. Velur generated updated schematics for all architectures (in this document) detailing the exact surface counts, summarized in Tables 2-4. These results were interpreted for emissivity control by A. Bouchez in KAON 501.</td>
</tr>
<tr>
<td>Split Relay</td>
<td>Need model to determine if split relay option fits (due to El bearing interference)</td>
<td>V. Velur investigated the packaging constraints that split relay imposes upon DNIRI and the LGS WFS package (to be documented in upcoming KAON). Compared to original concept, the LGS WFS pickoff was moved behind the DNIRI pickoff (see Figure 1).</td>
</tr>
<tr>
<td></td>
<td>Can LOWFS achieve req’d tip/tilt error on sci instruments (given the apparently significant non-common path features (tip/tilt mirrors, rotators, ADC)</td>
<td>D. Gavel and B. Bauman drafted a memo describing the challenges and potential solutions to non-common-path TT errors (to be incorporated into V. Velur’s upcoming Split Relay KAON).</td>
</tr>
<tr>
<td></td>
<td>Could MEMS be significantly more or less expensive than assumed in our differential cost comparison</td>
<td>D. Gavel contacted BMC and received updated quotes on 32 x 32 and 64 x 64 MEMS DM’s that were consistent with our internal cost estimates (see D. Gavel for details, if interested)</td>
</tr>
<tr>
<td>Adaptive Secondary Mirror</td>
<td>Might rank higher if broad community demand for add’l benefits of an ASM to existing instruments could be documented (e.g. write a short note on benefit to MOSFIRE.)</td>
<td>Not subsequently considered due to lack of time.</td>
</tr>
<tr>
<td>Large Relay</td>
<td>Confirm large DM costs</td>
<td>D. Gavel contacted Xinetics and CILAS with inquiries. CILAS responded with a ROM quote that was somewhat, but not significantly, higher than our internal estimate (see D. Gavel for details, if interested.)</td>
</tr>
<tr>
<td></td>
<td>Can the optical design meet the needs of Keck Interferometer?</td>
<td>C. Neyman considered the optical performance of a version of Large Relay (generated at Indian Wells in April 2006), that met the polarization and other requirements for KI (see KAON 483). Conclusion was that Large Relay could support KI (so no need for an auxiliary AO system to support KI)</td>
</tr>
<tr>
<td>Keck 1 Upgrade Path</td>
<td>What is the minimum technical field of view required for LOWFS NGS?</td>
<td>R. Dekany considered the degradation in performance that would be suffered with only 120” TFOV (KAON 504). It was concluded that 180” TFOV was required, a result that somewhat increases the cost of Keck 1 Upgrade architecture.</td>
</tr>
</tbody>
</table>

---

13 Any number of new data, such as successful go-to AO control demonstration, where thought capable of affecting our rankings, but we limited our concern to questions that could be answered in 4-6 weeks, the time available in the schedule before making an architecture baseline decision.
<table>
<thead>
<tr>
<th>Need a ‘convincing’ upgrade plan (that would not suffer from significant loss of AO observing time)</th>
<th>P. Wizinowich documented a potential upgrade sequence and schedule in KAON’s 500. The conclusion was that all areas of programmatic concern raised herein can be addressed (for example, by developing a lab development copy of the K1 AO system, which could still re-use components from the summit, to minimize down-time. These mitigations, however, increase the cost of the Keck 1 Upgrade option.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Need more careful analysis of re-engineering costs, including review by the Keck AO team and Sean Adkins</td>
<td>To be addressed in subsequent cost estimation by D. Gavel.</td>
</tr>
<tr>
<td>Cascaded Relay</td>
<td>Need a feasible optical design and packaging concept</td>
</tr>
<tr>
<td>Can the optical design meet the needs of Keck Interferometer?</td>
<td>C. Neyman considered this in parallel to answering the same question for Large Relay. The conclusion was that if we also have some freedom to make simple reconfigurations on the legacy Keck 2 AO system, then it and Cascaded Relay could likely be made to support Keck Interferometer’s needs (probably with pickoff from the collimated space after the DM in the 1st relay.)</td>
</tr>
<tr>
<td>Surface counts / Transmission</td>
<td>Subsequent analysis by A. Bouchez (KAON 501) showed that Cascaded Relay had 10% (absolute) lower optical transmission to the narrow-field instrument focal plane than Split Relay (with similar losses for DNIRI, but lessor differential for LGS HOWFS). At the 8/23/07 system architecture, these concerns were discussed, but the consensus was that the lower transmission was an acceptable trade-off in order to gain the lower technical risk, easier mechanical packaging, and more robust set of programmatic options in the face of an uncertain funding profile. (The potential increase in cost of laser power, relative to Split Relay somewhat offsets the notional $1.5M differential cost benefit tallied in Figure 6).</td>
</tr>
</tbody>
</table>

**Table 1.** Issues consider to be potentially influential in altering our initial architecture evaluation rankings, and there subsequent findings.
14. Candidate Architecture Surface Counts$^{14}$

14.1. Assumptions

In order to make an apples-to-apples comparison of the five architectures the following assumptions were made:

1. DNIRI has the TT sensors packaged into it. Which makes all the narrow field instruments look through its dichroic pick off. Alternately one could envision a separate TT sensor package dedicated to the narrow field instruments (this is not considered in this document).

2. DM’s are on TT stages where ever necessary, no extra surfaces are used for TT except in case of large DMs (K1 upgrade and Large Relay). A second TT stage is assumed in case of large relays to equalize the TT bandwidth between the architectures. DNIRI has its own TT stage (MEMS DMs can be mounted on this TT stage if we use MEMS DM’s) to allow for dithering. It is assumed that buying more stoke on the DM to use its surface for TT correction is more expensive than using a stage. It is assumed that the Adaptive Secondary has enough TT bandwidth.

3. All AO relays are reflective, the MEMS DM has a sapphire window on it and hence contributes to 5 surfaces when light bounces off of it.

4. A Risley prism pair based ADC design is assumed. For all other architectures the ADC is used only for the narrow field science path.

5. There are two enclosure windows to prevent condensation on the cold AO system in all cases except the ASM. The ASM option has the least number of surfaces and hence may need to get cooled lesser and so may be able to achieve performance with just one window.

6. In case of cascaded relay, the K mirror is in front of the large relay for convenience. So both LGS WFSs and DNIRI are stationary.

7. PSF camera pick offs are not considered for surface count and it is envisioned that acquisition camera pick-off moves out of the way during science observations.

Based on these assumptions, detailed surface counts follow in the following tables.

---

$^{14}$ For quantitative transmission and emissivity models, including surface-by-surface properties, refer to KAON 501.
14.2. Sky-to-Narrow Field Science Instrument Input

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Tel.</th>
<th>N.F. AO</th>
<th>W.F. AO</th>
<th>K Mirror</th>
<th>Na Dichroic</th>
<th>DNIRI Pickoff</th>
<th>ADC</th>
<th>2nd TT</th>
<th>Ent. Win.</th>
<th>Sci. Fold</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Split Relay</td>
<td>3</td>
<td>3+4</td>
<td>-</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>6</td>
<td>-</td>
<td>4</td>
<td>1</td>
<td>27</td>
</tr>
<tr>
<td>ASM</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>2</td>
<td>6</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td></td>
<td>14</td>
</tr>
<tr>
<td>Large Relay</td>
<td>3</td>
<td>-</td>
<td>3+1†</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td></td>
<td>26</td>
</tr>
<tr>
<td>K1 Upgrade</td>
<td>3</td>
<td>3</td>
<td>4‡</td>
<td>2</td>
<td>2</td>
<td>6</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td></td>
<td>29</td>
</tr>
<tr>
<td>Cascaded Relay</td>
<td>3</td>
<td>3+4⁰</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>6</td>
<td>-</td>
<td>4</td>
<td>1</td>
<td></td>
<td>31</td>
</tr>
</tbody>
</table>

Table 2. Table of surface count to the narrow-field science instrument for different NGAO candidate architectures; * - DM is already counted as part of NF AO relay, † - MCAO option, ‡ - extra fold mirror due to packaging constraint, †† - assume instruments all rotate, ⁰ - 4 more surfaces due to the MEMS DM in a hermetically sealed window package (may be revisited during preliminary design.)

14.3. Sky-to-DNIRI Input

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Tel.</th>
<th>N.F. AO</th>
<th>W.F. AO</th>
<th>K Mirror</th>
<th>Na Dichroic</th>
<th>DNIRI Pickoff</th>
<th>ADC</th>
<th>2nd TT</th>
<th>Ent. Win.</th>
<th>Sci. Fold</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Split Relay</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>8</td>
</tr>
<tr>
<td>ASM</td>
<td>3</td>
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<td>-</td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>Large Relay</td>
<td>3</td>
<td>-</td>
<td>3+1†</td>
<td>3</td>
<td>1</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>16</td>
</tr>
<tr>
<td>K1 Upgrade</td>
<td>3</td>
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<td>4‡</td>
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<td>2</td>
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<td>-</td>
<td>1</td>
<td>4</td>
<td>-</td>
<td>16</td>
</tr>
<tr>
<td>Cascaded Relay</td>
<td>3</td>
<td>-</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td></td>
<td>14</td>
</tr>
</tbody>
</table>

Table 3. Table of surface count to DNIRI for different NGAO candidate architectures; † - MCAO option, ‡ - extra fold mirror due to packaging constraint, - assume DNIRI rotates.

14.4. Sky-to-LGS WFS Input

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Tel.</th>
<th>N.F. AO</th>
<th>W.F. AO</th>
<th>K Mirror</th>
<th>Na Dichroic</th>
<th>DNIRI Pickoff</th>
<th>ADC</th>
<th>2nd TT</th>
<th>Ent. Win.</th>
<th>Sci. Fold</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Split Relay</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2⁰†</td>
<td>8</td>
</tr>
<tr>
<td>ASM</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6</td>
</tr>
<tr>
<td>Large Relay</td>
<td>3</td>
<td>-</td>
<td>3+1†</td>
<td>3</td>
<td>1</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>16</td>
</tr>
<tr>
<td>K1 Upgrade</td>
<td>3</td>
<td>-</td>
<td>4‡</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>-</td>
<td>1</td>
<td>4</td>
<td>-</td>
<td>18</td>
</tr>
<tr>
<td>Cascaded Relay</td>
<td>3</td>
<td>-</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 4. Table of surface count to the LGS WFS’s input for different NGAO candidate architectures; † - MCAO option, ‡ - extra fold mirror due to packaging constraint, †† - one window before the LGS WFS’s and another before it into the AO enclosure, † - assume LGS WFS’s rotate, ⁰ - using established space for ADC (might be feasible to build an exchanger to pull ADC out for DNIRI observations).
15. **Final Ranking Process and Baseline Selection**

As described in our original methodology (in the WBS 3.1.3 Work Scope Planning Sheet), the weeks following the System Architecture Retreat were used to address the outstanding issues, as described above. Face-to-face technical meetings were held on August 2, 2007 at Caltech and on August 9, 2007 at UCSC, at which progress on our outstanding issues was evaluated. These meetings, along with 3 additional team teleconferences provided ample opportunity for all participants to raise other areas of concern that could affect our initial architecture evaluation rankings, but no additional issues were identified that would materially impact our evaluation rankings.

At the same time, we continued development of updates to both the Science Requirements Document (ScRD, working on release 2) and the System Requirements Document (up to version 1.13). In addition, a meeting of the AOWG was convened by Michael Liu on August 16, 2007 at which some of the outstanding technical (and science requirements) questions were raised with a somewhat broader circle of AO experts. The feedback from the AOWG (see Liu’s minutes of the meeting) was helpful in providing guidance on certain system requirements, but did not uncover any issues substantive to our architecture rankings.

Finally, on August 23, 2007, the System Architecture Team met again by videoconference to review all newly collected information or analytical results pursuant to the architecture retreat. Relative to our preliminary rankings, there was some discussion of promoting the Keck 1 Upgrade architecture to 2nd place (above Split Relay) based on our better understanding of the mechanical challenges of Split Relay (interference with the El bearing) and a more realistic look at a detailed upgrade plan made in KAON 500. Some of the team thought that in order to address the potential disruptions to on-going AO observing, the Keck 1 Upgrade plan of KAON 500 had evolved into a potential re-use plan for the other architectures. All agreed that some aspects of NGAO, if developed early and implemented as a minor upgrade to Keck 1 AO, could improve on-going science returns. In the end, the relative evaluation of Split Relay and Keck 1 Upgrade was left unchanged.

Based on our best understanding of the requirements, technical risks, instrumentation goals, and costs the Keck NGAO System Architecture Team made the final architecture evaluation ranking:

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Final Ranking</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cascaded Relay</td>
<td>#1</td>
<td><strong>Adopted as NGAO Baseline Architecture</strong> and will be carried forward through remainder of the NGAO System Design Phase.</td>
</tr>
<tr>
<td>Split Relay</td>
<td>#2</td>
<td>Could deserve reconsideration upon the successful demonstration of go-to control on the sky and development of a feasibly compact DNIRI design, in order to potentially gain optical transmission advantage over Cascaded Relay</td>
</tr>
<tr>
<td>Keck 1 Upgrade</td>
<td>#3</td>
<td>Will be carried as an avenue for early NGAO program science return and as an NGAO alternative in the most pessimistic funding scenarios.</td>
</tr>
<tr>
<td>Large Relay</td>
<td>#4</td>
<td>This study confirms the feasibility of Large Relay (the concept described in the June 2006 NGAO study proposal to Keck Observatory), but has identified lower cost and more flexible architecture solutions.</td>
</tr>
<tr>
<td>Adaptive Secondary Mirror</td>
<td>#5</td>
<td>Deemed too expensive and too technically risky to meet NGAO Science Requirements.</td>
</tr>
</tbody>
</table>

Table 5. Final NGAO System Architecture Rankings.
# Appendix 1. NGAO System Architecture Work Scope Planning Sheet

## NGAO System Design Phase: Work Scope Planning Sheet v2.0

<table>
<thead>
<tr>
<th>WBS Element Title:</th>
<th>NGAO System Architecture Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>WBS Element Number:</td>
<td>3.1.3</td>
</tr>
<tr>
<td>Work Package Lead:</td>
<td>Richard Dekany</td>
</tr>
<tr>
<td>Work Package Participants:</td>
<td>Bauman, Gavel, Flicker, Neyman, Velur, Wizinowich</td>
</tr>
</tbody>
</table>

### Work Scope

**WBS Dictionary Entry:** Produce Baseline NGAO System Architecture and Program Scope in consideration of input from the system/science requirements, performance budgets and trade studies, and iterate with these efforts. Provide top-level guidance on architectural choices that meet the requirements, in order to allow the designs of the major systems (AO system, LGS facility, science operations and science instruments) to proceed. Document the system architecture considerations, trade-offs and decisions in support of the system design manual.

**Inputs:**
- System Requirements Document Rev 2.0
- Detailed NGAO Observing Scenario Use Cases
- The set of WBS 3.1.1 Performance Budget Tools and Reports
- Numerous WBS 3.1.2 Trade Study Reports
- Draft Operational Requirements Functional Requirements
- Science Instrument Priorities (updated from 6/06 proposal ranking)
- On-going Science Team Feedback (via in particular Claire)

**Products:**
- Documentation of the architecture selection process and selection criteria
- System Design Manual v1.0
- Functional Requirements Document v1.0 for the AO and laser systems
- Initial subsystem cost estimates
- Technical risk analysis v1.0

**Methodology:**
This work package will be executed by a small team (6 persons) working on a regular Monday afternoon meeting cadence (2-3 hour Wednesday meeting followed by ~10 hrs of additional work per person per week.) All meetings will be by video, with as frequent collection of team members in one location as possible (suggest Wednesday face-to-face meetings for Bauman, Dekany, Gavel, Velur when possible)

**Work Plan:**
May 24, 2007

- Review WBS 3.1.3 Plan
- Review Constraints from SRD
  - *KI support*
  - *Science instrument priorities (updated from 6/06 proposal ranking)*
- Review potential top-down architectures
  - *Keck 1 upgrades*
  - *Large FoV Relay, instruments, d-IFU*
Small FoV Relay(s), instrument d-IFU
AM2 / no AM2

May 30, 2007

Develop subsystem selection process and selection criteria
_Examples:_ Cost, cost risk, schedule risk, reliability, maintainability, vendor options, and system expandability

Discuss and adopt relevant list of system functions (see Table 1 for an example starting point)
_The definition of system functions should follow the System Requirements Document and the collection of NGAO Observing Scenario Use Cases._

Assign functions to team members, who will suggest, develop, and later rank candidate subsystems (resources include KAON library, literature, experience)

Schedule flow-down interviews with subsystem assignees

Tuesday, June 5, 2007 (Velur traveling)

First batch candidate subsystems described by assignees
- Includes initial evaluation against selection criteria
- Identify constraints and conditions on subsystem candidates that justify this ranking
  _Example:_ Subsystem A is only preferred under conditions B, C, and D. (Could be other subsystem choices or certain risk mitigation successes.)

Assign development of subsystem cost estimate basis template (for later ease of estimation)

June 13, 2007 (Velur and Dekany traveling)

Second batch candidate subsystems described by assignees
- Includes initial evaluation against selection criteria
- Includes cost estimate basis

June 20, 2007 – No Meeting (OSA conflict)

June 27, 2007

Review and adopt subsystem candidate rankings
- Address questions raised during initial evaluations

Define architecture evaluation criteria
_Examples:_ Cost, cost risk, schedule risk, performance, reliability, maintainability, vendor options, and system expandability
July 9-13, 2007 – Architecture Retreat

Propose candidate architectures as combinations of subsystems having top ranking determined above.
   Include original top-down architectures
   Brainstorm on new subsystem combinations

Develop architecture system-level cost estimation (parametric)

Assign and begin drafting initial Subsystems Functional Requirements Documents

July 25, 2007

Discuss and generate initial rank order candidate architectures in terms of architecture selection criteria.

Identify and assign key outstanding architecture issues to address

Aug 1, 2007

Review resolution of key issues, collect into Risk Register

Solicit external input as appropriate (e.g. latest guidance from Advancement Office)

Aug 8, 2007

Review external considerations

Collect architecture elements into prioritized, initial cost estimated program; input into SDM v1.0

**Formally adopt baseline architecture and program scope**

Assign SDM v1.0 writing assignments

Aug 15, 2007

Initial draft sections of SDM v1.0 due to SDM Editor

Aug 22, 2007

Final SDM section input, editorial review

Aug 29, 2007

Initial release of SDM v1.0 (WBS 3.6.1)
Initial release of Technical Risk Analysis v1 (WBS 3.1.3.4)

Estimate of effort: 3.1.3.1 Candidate Subsystems (subtotal = 480 hrs)
3.1.3.1 Define Candidate Subsystems = 228 hr (6 x 12 x 2 + 24 add’l management (keeping things moving, Dekany) + 60 consultations outside 3.1.3. team)

3.1.3.2 Subsystem Performance Evaluation = 72 hrs (3 x 12 x 2, Dekany, Gavel, Wizinowich)

3.1.3.3 Subsystem Cost Evaluation = 72 hr (3 x 12 x 2, Bauman, Neyman, Velur)

3.1.3.4 Subsystem Risk Analysis = 36 hr (3 x 12 x 1, Bauman, Neyman, Velur)

3.1.3.5 Organize Candidate Subsystems = 72 (6 x 12 x 1)

3.1.3.2 Candidate Architectures (subtotal = 586 hrs)

3.1.3.2.1 Define Candidate Architectures = 358 hr (6 x 12 x 2 + 16 add’l management (keeping things moving, Dekany) + 30 consultations outside 3.1.3. team + 6 x 20 architecture retreat + 6 x 8 one add’l face-to-face mtg)

3.1.3.2.2 Architecture Performance Evaluation = 72 hrs (3 x 12 x 2, Dekany, Gavel, Wizinowich)

3.1.3.2.3 Architecture Cost Evaluation = 72 hr (3 x 12 x 2, Bauman, Neyman, Velur)

3.1.3.2.4 Architecture Risk Analysis = 36 hr (3 x 12 x 1, Bauman, Neyman, Velur)

3.1.3.2.5 Adopt Baseline Architecture = 48 hr (6 x 8 x 1)

3.1.3.3 Functional Requirements (subtotal = 400 hrs)

3.1.3.3.1 Draft Functional Requirements Document = 20 hr Wizinowich

3.1.3.3.2 AO System Functional Requirements (subtotal = 240)

3.1.3.3.2.1 AO Functional Requirements Ver 1 = 160 hr (5 x 8 x 4 weeks, Johansson, Dekany, Gavel, Neyman, Wizinowich)

3.1.3.3.2.2 AO Functional Requirements Ver 2 = 80 hr (5 x 8 x 2 weeks, Johansson, Dekany, Gavel, Neyman, Wizinowich)

3.1.3.3.3 Laser System Requirements (subtotal = 140 hr)

3.1.3.3.3.1 Laser Functional Requirements Ver 1 = 92 hr (3 x 8 x 4 weeks, Chin, Velur, Johansson)

3.1.3.3.3.2 Laser Functional Requirements Ver 2 = 48 hr (3 x 8 x 2 weeks, Chin, Velur, Johansson)

3.1.3.4 Technical Risk Analysis (subtotal = 40 hrs)

3.1.3.4.1 Technical Risk Analysis Ver 1 = 20 hrs (Neyman)

3.1.3.4.2 Technical Risk Analysis Ver 2 = 20 hrs (Neyman)

(Editorial labor for SDM writing contained in 3.6.1)

Grand Total = 1,506 hours
## Appendix 1. NGAO System Functional Breakdown

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<td>System Wavefront Compensation</td>
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<td>Self Test &amp; Diagnostics</td>
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<tr>
<td>Science</td>
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</tbody>
</table>

This functional breakdown, developed by Chris Neyman, maps the NGAO system function (left) with the active subsystems (top). This input was used in the development of candidate subsystems that meet all of the NGAO system functional needs.
Appendix 2. NGAO Candidate Subsystem and Architecture Evaluation Criteria

Our subsystem evaluation criteria were developed and debated during a system architecture team meeting held on 5/30/07, and shown in order of importance (highest being most important.) In our deliberations, we elected to rank operations cost higher than development cost, reflecting a consensus of the importance of minimizing the on-going impact to Observatory operations beyond an initial NGAO capital campaign.

<table>
<thead>
<tr>
<th>Evaluation Criteria</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance Margin</td>
<td>Does this option meet the performance requirements and how much margin is there?</td>
</tr>
<tr>
<td>Operations Cost</td>
<td>Will this lead to low operations costs (procurement dollars and operations personnel costs)? This should include maintainability.</td>
</tr>
<tr>
<td>Development Cost</td>
<td>What are the relative development costs (dollars)?</td>
</tr>
<tr>
<td>Cost Risk</td>
<td>Is the risk to the development or operation costs low?</td>
</tr>
<tr>
<td>Technical Risk</td>
<td>Is the risk to not meeting the performance requirements low?</td>
</tr>
<tr>
<td>Reliability</td>
<td>Is the reliability of this option high? In particular, with respect to up-time of the system.</td>
</tr>
<tr>
<td>Interfaces</td>
<td>Does this option impose a minimum of physical requirements and constraints (physical space required, cabling, power, cooling, thermal management, ease of implementation on telescope, etc.)?</td>
</tr>
<tr>
<td>System Expandability</td>
<td>Is this option easily scalable and does it offer future capabilities?</td>
</tr>
<tr>
<td>Upgrade Applicability</td>
<td>Can this option be implemented on the current Keck AO systems? Consider the downtime to implement these upgrades in the evaluation.</td>
</tr>
<tr>
<td>Rankings</td>
<td>Poor, fair, good &amp; excellent.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cost Evaluation</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost Estimate (1st unit)</td>
<td>Rough Order of Magnitude cost in $k to produce the 1st unit. This should include all Non-Recurring Engineering (NRE) costs. All design, labor, subcontracts, prototype, lab test, etc. costs should be included.</td>
</tr>
<tr>
<td>Cost Uncertainty</td>
<td>It is adequate to have this at the +/- 50 or 100% level initially.</td>
</tr>
<tr>
<td>Unit Cost (2nd to nth unit)</td>
<td>ROM to build each subsequent unit.</td>
</tr>
<tr>
<td>Basis for Estimate</td>
<td>Any key information or assumptions used in estimating the costs.</td>
</tr>
</tbody>
</table>


During a subsequent architecture team meeting on 6/27/07, these same basic criteria were adopted, after considerable discussion, as our architecture evaluation criteria as well. We could not justify reordering of these criteria even though there were some arguments (typically made pairwise) for changing relative importance. It was recognized that additional work would be needed to incorporate programmatic criteria, however, and this open item was subsequently addressed during the System Design Retreat when the following programmatic criteria were added to augment the technical criteria in the table above, again in rank order of importance:
<table>
<thead>
<tr>
<th><strong>Programmatic Evaluation Criterion</strong></th>
<th><strong>Definition</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Match to Strategic Goals</td>
<td>To what extent does this architecture support the strategic goals of Keck Observatory, paraphrased as “High-angular resolution science”, “Efficient Operations”, and “World-class Instrumentation”</td>
</tr>
<tr>
<td>Early Science / Phasing Flexibility</td>
<td>How well does this architecture enable early science results that are unique and only possible using NGAO developments? How well does this architecture absorb uncertainties in the funding profile to enable a phased implementation of the full NGAO capability?</td>
</tr>
<tr>
<td>Facilitation of Pre-Telescope I&amp;T</td>
<td>How well does this architecture support integration and testing at the development site, prior to shipment to the summit?</td>
</tr>
<tr>
<td>Implementation Impact on AO Operations during development</td>
<td>To what extent would this architectural approach adversely affect on-going science operations, in terms of unavailable AO time, strain on key Observatory staff, etc.?</td>
</tr>
<tr>
<td>Development Tied to Observing Schedule</td>
<td>To what extent would the NGAO Project Plan be constrained by needing to fit into (or in between) on-going observing schedule constraints?</td>
</tr>
<tr>
<td>dNIRI only AO Costs</td>
<td>To what extent does this architecture allow for top-priority development of the dNIRI instrument, if total program funding is severely constrained?</td>
</tr>
<tr>
<td>Community Experience</td>
<td>Does the Keck instrumentation community have related experience, by specifically having demonstrated this architecture or key elements thereof?</td>
</tr>
</tbody>
</table>

**Table 7.** Architecture Programmatic Evaluation Criteria.

Other criteria discussed, but not confirmed as discriminators between alternative architectures, included the availability of program off-ramps (this was subsumed into Phasing Flexibility), and the divisibility of the program work among partner organizations (all architectures were deemed of sufficient scope and complexity to fully engage partner expertise).

---

15 These definitions were not written down during the System Architecture Retreat, but are believed to reliably capture the meaning of the criteria as they were assembled and ordered during interactive discussions.
We document here the candidate subsystem assessments that were input into the System Architecture work package. To protect confidentiality, ROM cost estimates for each candidate solution has not been reproduced in this KAON.

Keck Next Generation Adaptive Optics
Sub-system assessment, by functionality and implementation method
Don Gavel version 1.0 6/4/07

<table>
<thead>
<tr>
<th>Function</th>
<th>Method</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Correct High-Order</td>
<td>Performance Margin</td>
<td>Development Cost</td>
</tr>
<tr>
<td>Adaptive Secondary</td>
<td>Moderate (1)</td>
<td>Moderate</td>
</tr>
<tr>
<td>Piezo DM</td>
<td>Moderate (1)</td>
<td>Unknown</td>
</tr>
<tr>
<td>MEMS DM</td>
<td>Unknown</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

(1) Depends on the performance specifications for number of actuators and interactuator spacing
(2) Possibly good if we use the existing design (64x64), bad if a new design is needed, depending on the requirements

| Correct Tip-Tilt | | |
|-----------------|-----------------|
| Chopping / adaptive secondary | Moderate (3) | Good | Good | Good | Moderate | Good |
| DM on tip/tilt stage | Moderate (3) | Good | Good | Good | Good | Good |

(3) Require >30 Hz closed loop bandwidth to correct vibration and wind shake

Project Lasers: Laser
LMCT/Gemini S clone | Moderate | Good | Bad | Bad, depends | Moderate | Unknown | Moderate | Good |
SOR clone | Good | May need very costly development | Unknown | Bad, depends | Moderate | Good | Unknown | Good |
Pulsed | Good | Bad | Unknown | Bad, depends | Bad, depends | Unknown | Good | Good |

(4) Pulsed laser would deliver higher SNR wavefront per Watt due to a) spot elongation mitigation, b) Raleigh gating

Project Lasers: Beam Control Uplink AO
Uplink atmospheric AO correction | Very good (5) | Bad | Unknown | Bad | Bad | Unknown | Good | Compatible |
Uplink slow aberrations-only AO correction | Acceptable | Good | Good | Good | Good | Good | Good | Compatible |

(5) Uplink AO does potentially sharpen the spot for better centroiding, however performance gain is limited by LGS elongation and WFS subaperture diffraction

Ordinarily uplink AO would also use a larger launch telescope aperture to make a smaller spot - but this may be offset by the above consideration such that larger than the "usual" size (~30cm) would only produce diminishing returns

Project Lasers: Beam Projector
Variable asterism | Good (6) | Bad, potentially | Unkown | Bad, potentially | Moderate | Bad | Bad | Potentially Compatible |
Fixed set of asterisms | Bad | Acceptable | Acceptable | Acceptable | Acceptable | Good | Moderate | Compatible |
Single launch telescope with shared aperture | Good | Good | Good | Good | Good | Good | Compatible |
Multiple launch telescopes | Good | Good | Good | Good | Good | Good | Compatible |

(6) 140 nm total wavefront error narrow field
(7) Fratricide will adversely affect the LGS power needed to achieve a given SNR
Note: fratricide could be mitigated with pulsed lasers and proper gate-timing

Note: These assessments are subject to change as more detailed designs and analyses are developed.
### Subsystem Function = Tip-Tilt star pick-off

<table>
<thead>
<tr>
<th>Description</th>
<th>Optical switchyard</th>
<th>Fishing rod</th>
<th>Tiled focal plane</th>
<th>Kickbot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance Margin</td>
<td>Unsure</td>
<td>Very good</td>
<td>good/Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Operations Cost</td>
<td>Excellent</td>
<td>Very good</td>
<td>Very good</td>
<td>Very good</td>
</tr>
<tr>
<td>Development Cost</td>
<td>Good/Fair</td>
<td>Fair/good</td>
<td>Fair/good</td>
<td>Very good</td>
</tr>
<tr>
<td>Cost Risk</td>
<td>Excellent</td>
<td>Good</td>
<td>Fair</td>
<td>Fair</td>
</tr>
<tr>
<td>Technical Risk</td>
<td>good/Excellent</td>
<td>Good/very good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Reliability</td>
<td>Excellent</td>
<td>Very good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Interfaces</td>
<td>Very good</td>
<td>Good</td>
<td>Good</td>
<td>Very good</td>
</tr>
<tr>
<td>System Expandability</td>
<td>Fair/Good</td>
<td>Very good</td>
<td>Good</td>
<td>Very good</td>
</tr>
<tr>
<td>Upgrade Applicability</td>
<td>Excellent</td>
<td>Good</td>
<td>Fair</td>
<td>Good</td>
</tr>
</tbody>
</table>

**Evaluation Criteria**

- **Additional Criteria/Notes**: P3k development, that opts for an optical switchyard, is useful to this study for a start comparison. Not new technology but these must include a method of MEMS correction. Not new but would need prototypes developed for this application.

### Subsystem Function = On chip dithering

<table>
<thead>
<tr>
<th>Description</th>
<th>Optical switchyard</th>
<th>Fishing rod</th>
<th>Tiled Focal Plane</th>
<th>Kickbot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Performance Margin</td>
<td>Excellent</td>
<td>Good</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Operations Cost</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Excellent</td>
</tr>
<tr>
<td>Development Cost</td>
<td>Very good</td>
<td>Good/Fair</td>
<td>Fair</td>
<td>Fair</td>
</tr>
<tr>
<td>Cost Risk</td>
<td>Very good</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Technical Risk</td>
<td>Very good</td>
<td>Good</td>
<td>Good/Fair</td>
<td>Good/Fair</td>
</tr>
<tr>
<td>Reliability</td>
<td>Very good</td>
<td>Very good</td>
<td>Very good</td>
<td>Very good</td>
</tr>
<tr>
<td>Interfaces</td>
<td>Excellent</td>
<td>Fair/Good</td>
<td>Very good</td>
<td>Excellent</td>
</tr>
</tbody>
</table>

**Evaluation Criteria**

- **Additional Criteria/Notes**: In general this needs input from other areas- laser design, size of tip-tilt mirror, have we defined dither correctly. NB The criteria here JUST address the option for dithering and not as a way of doing TT star pickoff.
# Keck Next Generation Adaptive Optics

## Sub-system assessment, by functionality and implementation method

Evan Bauman

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</thead>
<tbody>
<tr>
<td>Optical relays</td>
<td>Reflective</td>
<td>very good</td>
<td>good for field size &lt; pupil size</td>
<td>low, unless using very large DMs (larger space requirements)</td>
<td>low</td>
<td>moderate</td>
<td>low</td>
<td>high</td>
<td>needs output format defined</td>
<td>limited to field-pupil diameter</td>
<td>limited to field-pupil diameter</td>
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<tr>
<td></td>
<td>Refractive</td>
<td>good (falls off at K)</td>
<td>good for field size &lt; 2 * pupil size</td>
<td>low</td>
<td>low</td>
<td>moderate</td>
<td>moderate</td>
<td>moderate</td>
<td>limited to field-pupil diameter</td>
<td>limited to field-2* pupil diameter</td>
<td></td>
</tr>
<tr>
<td>LGS WFS</td>
<td>split off via dichroic in front</td>
<td>very good</td>
<td>very good</td>
<td>very good</td>
<td>moderate (1)</td>
<td>moderate</td>
<td>moderate</td>
<td>moderate</td>
<td>moderate</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td></td>
<td>picked off after relay</td>
<td>very good, but could be limitations in field</td>
<td>very good, could suffer if field is much larger than pupil size</td>
<td>moderate (1)</td>
<td>moderate</td>
<td>moderate</td>
<td>moderate</td>
<td>moderate</td>
<td>good</td>
<td>good</td>
<td>fair</td>
</tr>
<tr>
<td>LOWFS</td>
<td>via pickoffs at front</td>
<td>very good</td>
<td>very good</td>
<td>very good</td>
<td>moderate (1)</td>
<td>moderate</td>
<td>moderate</td>
<td>moderate</td>
<td>moderate</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td></td>
<td>picked off after relay</td>
<td>very good</td>
<td>very good, could suffer if field is much larger than pupil size</td>
<td>moderate (1)</td>
<td>moderate</td>
<td>moderate</td>
<td>moderate</td>
<td>moderate</td>
<td>good</td>
<td>good</td>
<td>fair</td>
</tr>
</tbody>
</table>

(1) more open-loop development costs to split off in front; more optomechanical costs if after relay (optomechanics might not be possible, depending on requirements)
### Keck Next Generation Adaptive Optics

Sub-system assessment, by functionality and implementation method

Richard Dekany

#### Subsystem Function = Laser guide star architecture

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Array of Na beacons, reconfigurable between narrow and wide LGS asterisms, with independent patrolling d-IFU's</th>
<th>Array of Na beacons, reconfigurable between narrow and wide LGS asterisms, with independent patrolling d-IFU's plus add'l Na beacons pointable toward TT stars</th>
<th>Fixed narrow asterism of Na beacons for narrow FoR instruments, plus a pointable array of Rayleigh asterisms, one asterism per d-IFU channel and one asterism per TT star</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Evaluation Criteria</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Performance Margin | Fair | Good (TBC) | TBD
(TBC) |
| Operations Cost | Fair | Fair | Good |
| Development Cost | Poor | Poor | Good |
| Cost Risk | Fair | Fair | TBD |
| Technical Risk | Fair | Fair | Good |
| Reliability | Fair | Good | Good |
| Interfaces | Good | Good | Excellent |
| System Expandability | Good (high, but fixed, complexity for either few or many d-IFU's) | Good (high, but fixed, complexity for either few or many d-IFU's) | Excellent (complexity scales with number of d-IFU channels; part count grows approximately linearly with channel count) |
| Upgrade Applicability | Good (can start with less Na power, upgrade power as $'s become available) | Good (can start with less Na power, upgrade power as $'s become available) | |
| Additional Criteria/Notes | TT stars are sharpened to the extent that a good tomography solution can be found in that direction | TT stars are presumably sharpened somewhat better, using the pointable Na beacons to ‘tune up’ the tomography solution in the TT star direction | Preferred approach if a) performance margin can be met, and b) the total cost of deploying a Rayleigh LGS system for d-NIRI is considerably less than the incremental cost of a wide-field Na LGS system (over a narrow-field Na asterism system) |

It may be possible to use RLGs even for the narrow-field, high-Strehl system, in an architecture having a single 50 W Na beacon, surrounded by some modest number (11?) RLGs used only to compensate for focal anisoplanatism. This is somewhat speculative, but probably deserves a quick analysis, given the importance of choosing an appropriate laser architecture.
## Subsystem Function

**LGS mode low order wave front sensor**

<table>
<thead>
<tr>
<th>Candidate</th>
<th>2 IR Trackers + 1 TTFA IR-Pyramid</th>
<th>2 APD Tracker + 1 TTFA Shack</th>
<th>2 APD Tracker + 1 TTFA Pyramid (CCD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Evaluation Criteria</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Performance Margin</td>
<td>good</td>
<td>fair</td>
<td>poor (good see comments)</td>
</tr>
<tr>
<td>Operations Cost</td>
<td>good</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>Development Cost</td>
<td>fair</td>
<td>fair</td>
<td>good</td>
</tr>
<tr>
<td>Cost Risk</td>
<td>fair (poor)</td>
<td>fair (poor)</td>
<td>good (fair see comments)</td>
</tr>
<tr>
<td>Technical Risk</td>
<td>good</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>Reliability</td>
<td>good</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>Interfaces</td>
<td>fair</td>
<td>fair</td>
<td>good</td>
</tr>
<tr>
<td>System Expandability</td>
<td>fair (poor)</td>
<td>fair (poor)</td>
<td>fair</td>
</tr>
<tr>
<td>Upgrade Applicability</td>
<td>fair (poor)</td>
<td>fair (poor)</td>
<td>fair</td>
</tr>
<tr>
<td><strong>Final Ranking</strong></td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
</tbody>
</table>

**Additional Criteria/Notes**

- Same function as LGSmode TTWFS (see cell B1 comments)
- IR Tracker = IR Single Quad Cell or Single Pyramid (STRAP)
- IR TTFA has capability to measure Focus and Astigmatism but can be configured to just TT if needed
- Assume MEMS correction and tomography sensing/reconstruction
- Assumed Na guide stars + NGS

---

**Shack-Hartmann WFS (CCD) IR Tracker APD Tracker**

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Shack-Hartmann WFS (CCD)</th>
<th>IR Tracker</th>
<th>APD Tracker</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Evaluation Criteria</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Performance Margin</td>
<td>good</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>Operations Cost</td>
<td>good</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>Development Cost</td>
<td>fair</td>
<td>fair</td>
<td>fair</td>
</tr>
<tr>
<td>Cost Risk</td>
<td>good</td>
<td>fair (poor)</td>
<td>good (fair see comments)</td>
</tr>
<tr>
<td>Technical Risk</td>
<td>good</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>Reliability</td>
<td>good</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>Interfaces</td>
<td>fair</td>
<td>fair</td>
<td>good</td>
</tr>
<tr>
<td>System Expandability</td>
<td>fair</td>
<td>fair</td>
<td>fair</td>
</tr>
<tr>
<td>Upgrade Applicability</td>
<td>fair</td>
<td>fair</td>
<td>fair</td>
</tr>
<tr>
<td><strong>Might benefit from dedicated tracker</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

---

**LGS mode Truth Sensor**

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Large FOV imaging detector</th>
<th>small FOV imaging detector</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Evaluation Criteria</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Performance Margin</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>Operations Cost</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>Development Cost</td>
<td>fair</td>
<td>fair</td>
</tr>
<tr>
<td>Cost Risk</td>
<td>good</td>
<td>fair</td>
</tr>
<tr>
<td>Technical Risk</td>
<td>good</td>
<td>good</td>
</tr>
<tr>
<td>Reliability</td>
<td>good</td>
<td>fair</td>
</tr>
<tr>
<td>Interfaces</td>
<td>fair</td>
<td>fair</td>
</tr>
<tr>
<td>System Expandability</td>
<td>fair</td>
<td>fair</td>
</tr>
<tr>
<td>Upgrade Applicability</td>
<td>single head movable around field of regard</td>
<td>Use in focus and out of focus images, along with phase diversity algorithms to recover performance</td>
</tr>
</tbody>
</table>

**Additional Criteria/Notes**

- Might be on instrument wavefront sensor
- Might be science camera
- Might be PSF monitor camera
Appendix 3. System Architecture Retreat Agenda

Keck NGAO Team Meeting #8

9:00 a.m. – 6:00 p.m. (Pacific Daylight Time)
Mon., July 9 to Fri., July 13, 2007
Center for Adaptive Optics, UC Santa Cruz


Keck conference rooms
- Tues: Mauna Kea (P#128.171.99.74, 881 – 3500 console, 881 – 3806 backup)
- Wed–Fri: Kamuela (P#128.171.99.69, 881 – 3513 console, 881 – 3505 backup)

Directions: GAO web site (html) and Directions to the Center (html)

<table>
<thead>
<tr>
<th>In propria persona (full week)</th>
<th>Bauman, Dekany, Gavel, Max, Moore, Neyman, Vefur, Wizinowich</th>
</tr>
</thead>
<tbody>
<tr>
<td>In propria persona (partial week)</td>
<td>Le Mignant (Mon &amp; Tues), McFarland (Mon – Wed, Thur/Fri TBC)</td>
</tr>
<tr>
<td>In effigie (e.g. on the phone – partial week (all TBC...)</td>
<td>Akins (Mon pm Requirements summaries, Thurs pm Design choices &amp; FRD or Program structure), Bouchez (TBD), Britton (Mon am Requirements summaries), Chin (Tues &amp; Wed Reports, Thurs am Architecture ranking, Thurs pm Design choices &amp; FRD), Johansson (Mon Summaries, Tres &amp; Wed Reports, Thurs am Architecture ranking, Thurs pm Design choices &amp; FRD)</td>
</tr>
</tbody>
</table>

Action items from the meeting: Action items, Status of Action Items as of XXX.

Minutes:
- Claire’s notes: MondayNotes.txt, TuesdayNotes.txt, WednesdayNotes.txt, ThursdayNotes.txt
- Neyman’s notes: MondayNotes.doc

System Architecture Goals
- Identify & rank candidate architectures
- Develop architecture system-level cost estimation
- Progress on subsystem functional requirements
- Understanding of how the different architectures imply different program structures (for example, a Keck upgrade could offer an incremental approach to development & science return)

Reference Material
- System Requirements Summary (Wizinowich): Science Requirements Summary, Summary of Required Requirements Changes (SRR), SRR.

Architecture Report Contents:
- Revised working definition of each candidate architecture (e.g. marked up architecture poster)
- Summary of requirements satisfaction (e.g. areas of performance concern)
- Summary of technical pros and cons, including major risk items
- Initial LOM development cost estimate & subjective operations cost estimate

Candidate Architectures
- #1 SplitRelay – Split 20” Narrow field instruments / 120” ci-NIRI relay architecture
- #2 AMT – Active mirror secondary mirror architecture
- #3 LargeRelay – Single 200” ci-NIRI relay architecture working session
- #4 RI Uprates – Keck I upgrade path architecture
- #5 CascadeRelay – A variant of LargeRelay in which a 2nd stage is used for narrow-field instruments, reduces size
- #6 TBD

Retreat Agenda
- Mon, July 9 – Goal is to understand the requirements, particularly performance and science instrument reqs.
  - 8:45 am Arrival
  - 9:00 am Review agenda and meeting goals (including Report contents) (Dekany)
  - 10:00 am Summarize/review results of performance budgets (Britton)
  - 10:30 am Summarize/review results of trade studies (Neyman)

NGAO Systems Architecture
NGAO Systems Architecture

• 12:00 pm Lunch
• 1:00 pm Summarize/review science requirements impacting AO architecture – review summary tables (Max) *
• 2:00 pm Summarize/review science operations requirements impacting AO architecture (Le Migniot)
• 3:00 pm Review top-down candidate architectures (DeKany)
• 3:30 pm Working session #1 – Split 20' Narrow field instruments / 120’ d-NIRI relay architecture (Proposed: Bauman, Le Migniot, McGrath, Moore, Veilur, Wizinowich)
• 3:30 pm Working session #2 – Adaptive secondary mirror architecture (Proposed: DeKany, Gavel, Max, Neyman) KACN405 ASM Trade Study APM Schematic
• 6:00 pm Adjourn

Tues, July 10th ––– Goal here is to see how our top-down architectures measure up in terms of meeting reqs and using our favored subsystems

• 8:00 am Working session #1 (cont) - Split 10’ Narrow field instruments / 120’ d-NIRI relay
• 8:00 am Working session #2 (cont) - Adaptive secondary mirror
• 10:00 am Report #1 – Adaptive secondary mirror architecture (All) • 11:00 am Report #2 – Split 20’/120’ architecture (All)
• 11:30 pm Lunch at CFAO
• 12:30 pm Working session #3 – Single 180° TFOV relay architecture working session (Proposed: DeKany, McGrath, Moore, Neyman, Veilur)
• 12:30 pm Working session #4 – Keck upgrade architecture working session (Proposed: Bauman, Gavel, Max, Wizinowich) KACN461 Keck AO Upgrade Trade Study Keck AO Schematic
  • 4:00 pm – 5:00 pm Science Team Q&A Session (Law, Max, McGrath ?)
• 5:30 pm Report #3 – Single 180° TFOV relay architecture (All)
• 6:00 pm Report #4 – Keck upgrade architecture (All)
• 6:30 pm Dinner at CFAO

Wed, July 11th ––– Goal here is to allow new ideas to be pursued sufficiently (these may be small variations of a top-down approach)

• 8:00 am Brainstorm Session (All)
• 9:00 am Brainstorm Architecture #6 (Teams TBD)
• 9:00 am Brainstorm Architecture #6
• 12:00 pm Lunch
• 1:00 pm Brainstorm Architecture #5 (cont.)
• 1:00 pm Brainstorm Architecture #6 (cont.)
• 3:00 pm Report #5 – Architecture #5 (All)
• 3:30 pm Report #6 – Architecture #6 (AB)
• 4:00 pm Review Afternoon Assignments (All)
• 4:00 pm – 5:00 pm Science Team Q&A Session (Cancelled)
• 6:00 pm Adjourn

Thurs, July 12th ––– Goals here are to agree on architecture rankings and understand the context of our architectures in a larger program (e.g. costing and phasing)

• 8:30 am Review Previous Day Assignments (All)
• 10:00 am Initial Architecture Ranking Based on Evaluation Criteria <–– should this await the program discussion? Architecture Comparison
• 12:00 pm Lunch
• 1:00 pm Design Choices (what’s common and what’s architecture dependent) (Wizinowich)
• 2:00 pm Functional Requirements Document Overview (Wizinowich) FDR_v01
• 2:30 pm FDR Development working session
  • AO system architectural assumptions (Neyman)
  • Laser system architectural assumptions (Veilur)
  • AO system optical requirements (Neyman to define participants)
  • Laser system optical requirements (Veilur to define participants)
• 2:30 pm Program Structure working session (DeKany, Gavel, Max, Wizinowich)
• 4:00 – 5:00 pm Science Team Q & A Session (Barth, DeKany, Gavel, Max, McGrath, Wizinowich) (TBD)
• 5:30 pm Program Structure Report and Discussion (AB)
• 6:15 pm FDR Issues Discussion (All)
• 7:00 pm Dinner at CFAO

Fri, July 13th ––– Goal here is to set stage for next steps.

• 8:30 am Science Team Report / Issues
• 9:45 am Design Choices (what’s common and what’s architecture dependent) (Wizinowich)
• 9:45 am – 1:00 pm Work on System Architecture Options Summary (Moore, McGrath)
• 10:45 am Functional Requirements Document Overview (Wizinowich) FDR_v01
• 11:30 am FDR Development working session
  • AO system architectural assumptions (Neyman)
  • Laser system architectural assumptions (Veilur)
  • AO system optical requirements (Neyman to define participants)
  • Laser system optical requirements (Veilur to define participants)
• 11:30 am Program Structure working session (DeKany, Gavel, Max, Wizinowich)
• 12:00 pm Lunch
• 2:30 pm Program Structure Report and Discussion (AB)
• 3:00 pm FDR Issues Discussion (All) • FDR_cadline.doc
• 3:30 pm Action Items & Schedule Summary (AB)
• 4:00 pm Adjourn (Whoever is left)
FRD Development Resources and Drafts

* 070713_NGAO_FRD_Design_Choices.pdf: Summary of commonality between top-ranked architectures as of 070713

Show attachments (24)

This topic: Keck/NGAO > 070709_UCSC_NGAO_Meeting_8

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Ideas, requests, problems regarding TWiki? Send feedback.
Appendix 4. Original System Architecture Retreat (Team Meeting #8) Schematics

Figure 7: Original schematic of the “Split Relay” system architecture generated 7/9/07.

Figure 8. P. Wizinowich’s original schematic layout for the Adaptive Secondary architecture
Figure 9. Original schematic of the "Large Relay" System Architecture. (Reference also the June 2006 NGAO proposal which also presented a feasibly optical layout and packaging design fitting the relay and 3 simultaneously mounted instruments on the Nasmyth platform.)

Figure 10. A. Moore’s original “LEGO block” configuration schematic for instruments fed by the Large Relay. Note, DNIRI is missing from this diagram, but could be fed as an instrument ahead of the ‘lego stack’ (e.g. off to the right), or as an instrument ‘behind’ the Vis Imager shown (potentially excluding one of the five NGAO instrument concepts from simultaneous co-mounting.)
Figure 11. A reference depiction of the current Keck Adaptive Optics system used for discussion of the Keck 1 Upgrade Path architecture.