NGAO System Architecture Definition

KAON #499

Version 1.2
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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.

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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 SRD[1] and Detailed Observing Scenario Use Cases[2]
- Define Subsystem Evaluation Criteria[3]
- 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[4]
- Define Architecture Evaluation Criteria
  - Propose Candidate Architectures as Different Combinations of High-Ranking Candidate Subsystems
  - Develop Rough Order of Magnitude (ROM) Differential (Parametric) Cost Estimates for the Candidate Architectures
  - 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[5]

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

[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.

6. System Architecture 1: The "Split Relay"

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[7]
  - 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)

[7] 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.

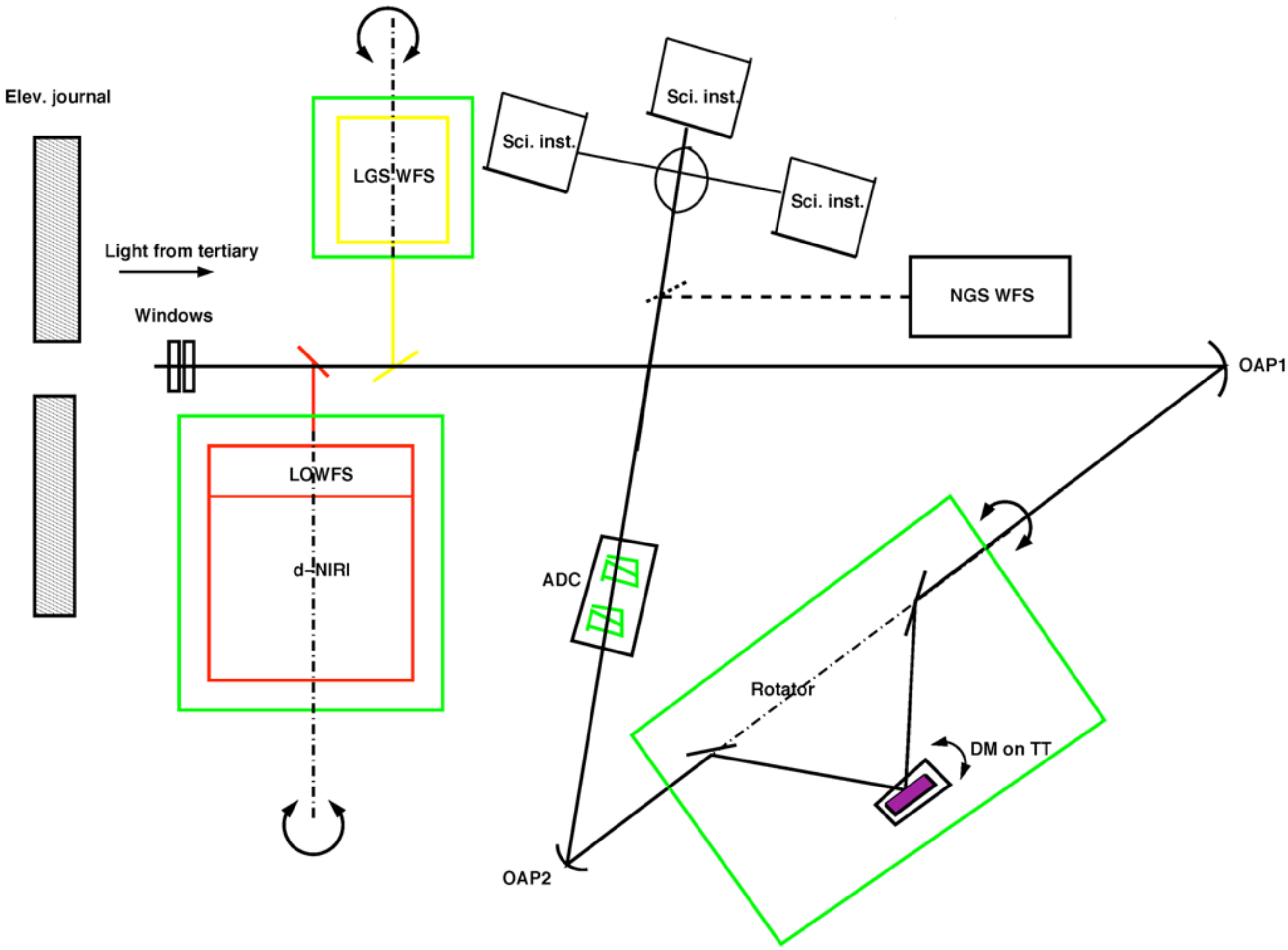

Figure 1. A schematic layout of the Split Relay architecture. [In this and subsequent schematic layouts color coding is used to represent different features. Optics/ subsystems shown in green rotate, MEMS DM's are magenta in color while piezo DMs are blue colored. DNIRI/ TT pick off and path are shown 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 TTMs, 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 employes 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 sinsgle k-mirror field de-rotator.

7. System Architecture 2: The "Adaptive Secondary Mirror"

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.

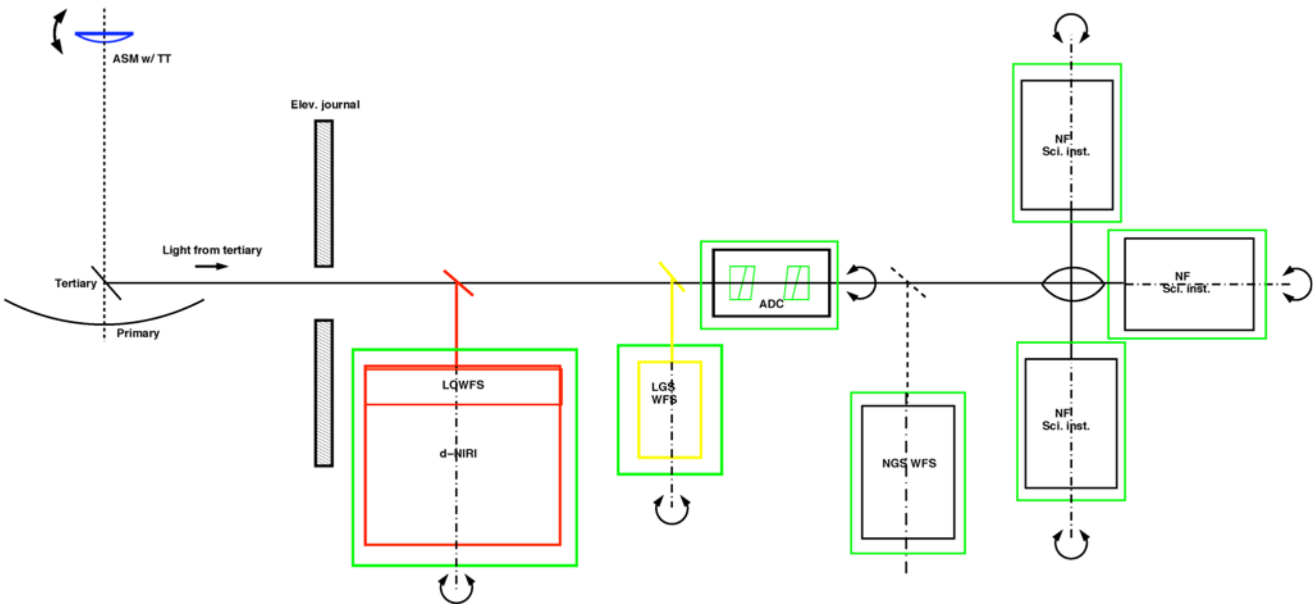

Figure 2. A schematic layout for the Adaptive Secondary architecture

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 theis 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 El 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-Chrietien 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 seem 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 achiteve 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.

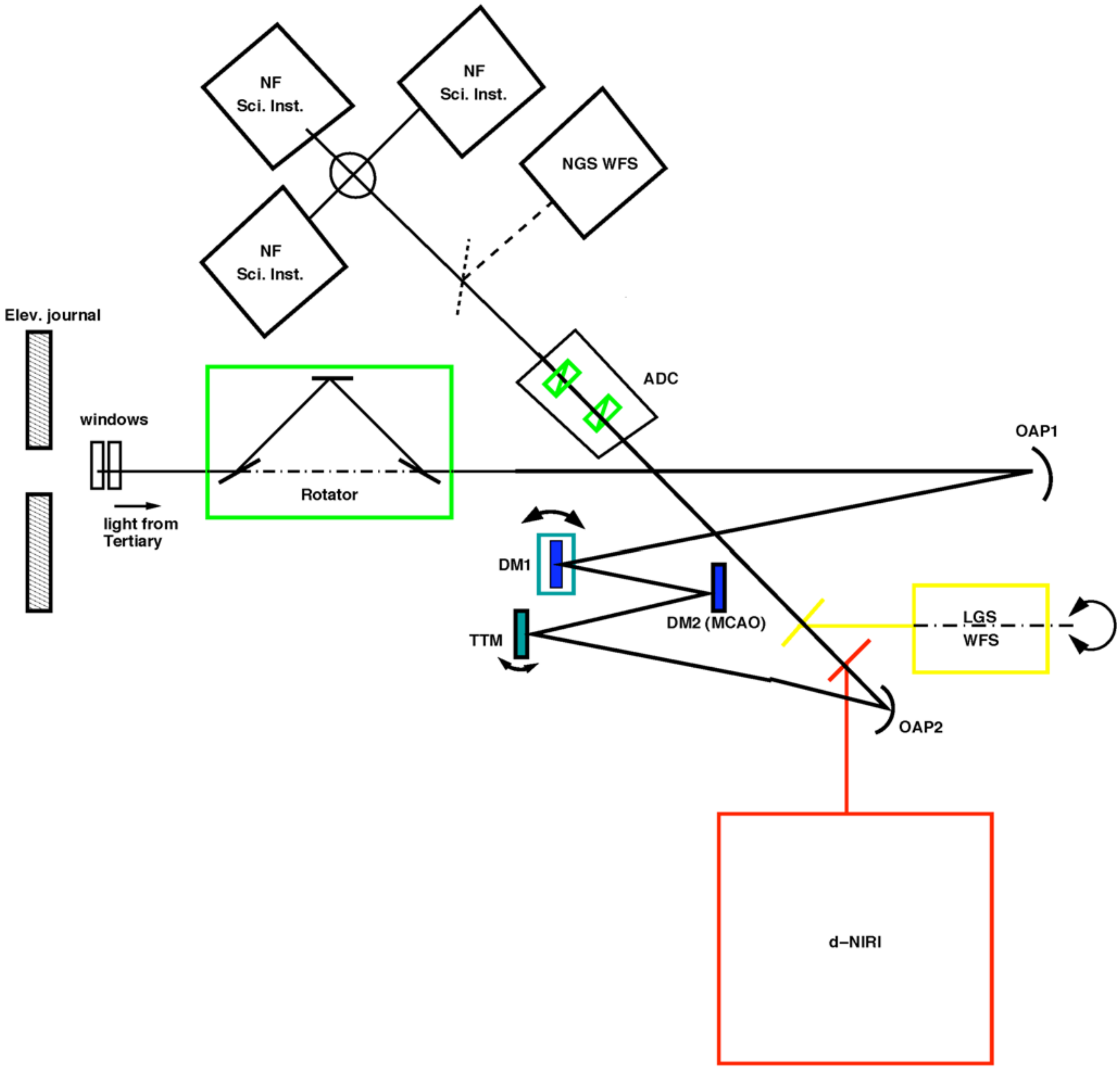

Figure 3. A schematic layout of the Large Relay architecture.

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.

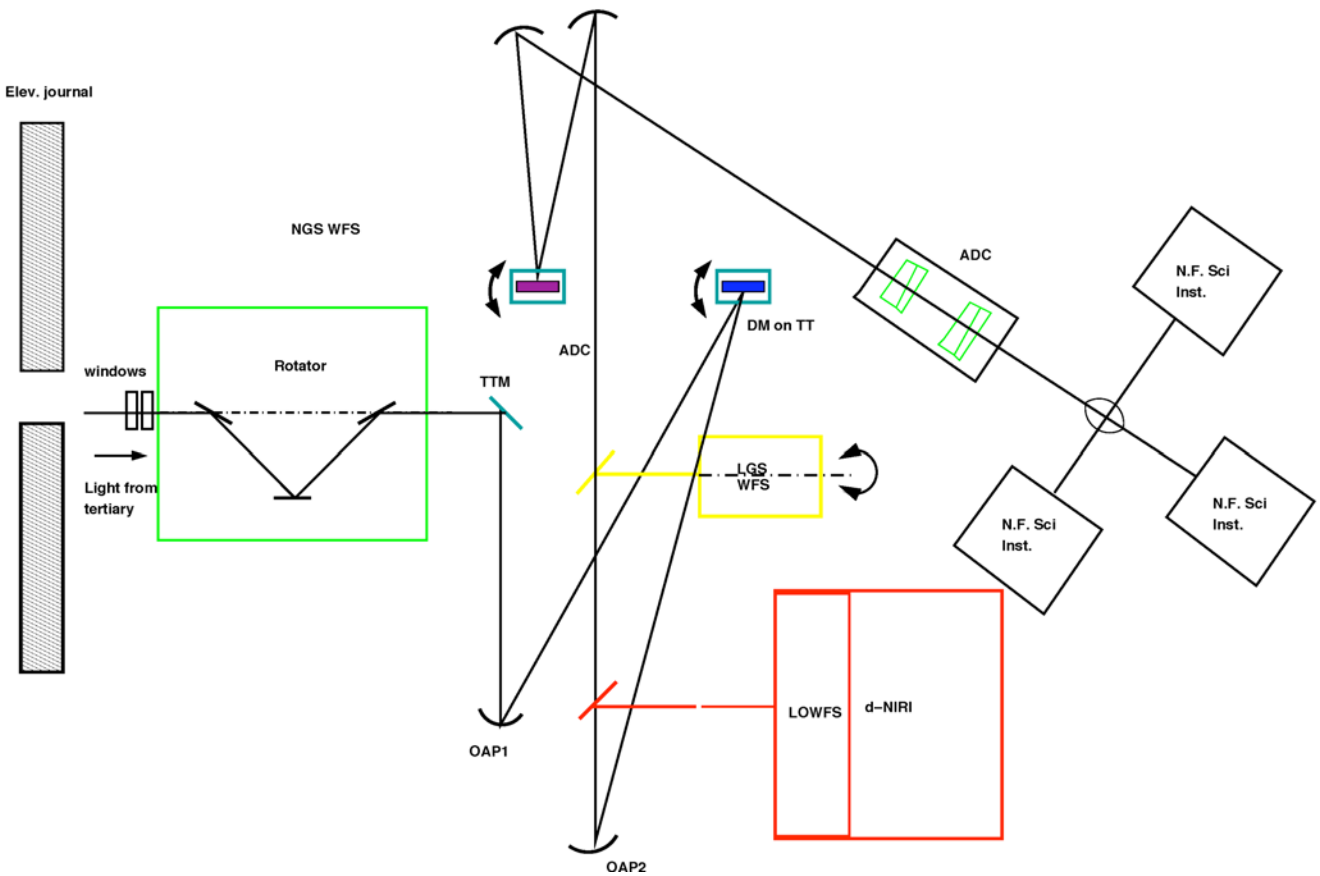

Figure 4. A schematic layout of the Keck 1 Upgrade Path architecture. The magenta rectangle represents a small diameter MEMS DM (mounted on a tip/tilt stage) embedded in a new 2nd OAP relay that follows an upgraded form of the existing Keck 1 AO system. The NGS WFS is not shown on this figure, but could 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.

- o 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.
  - o 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
  - o 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.
  - o 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.
  - o 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
  - o A 64x64 DM the same size as the existing DM would likely be expensive.

- o Could relatively easily upgrade to a 40x40 DM with 3.5 mm pitch (and perhaps this is adequate for NGAO?).
- o 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 Mignant, 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.)

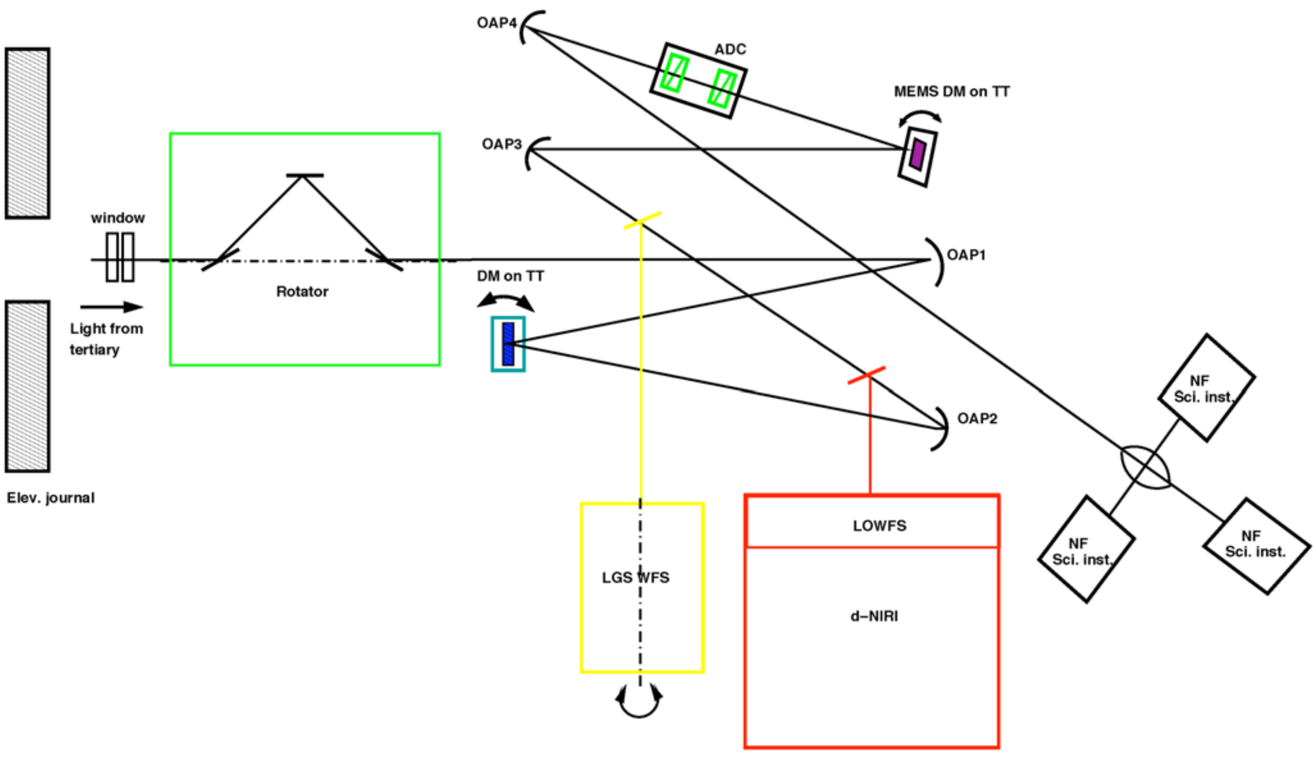

Figure 5. A schematic layout for the Cascaded Relay architecture. The NGS WFS (not shown) would sample the light downstream of OAP4, but before the back-end instrument stack, with an NGS patrol field of 30" circular diameter.

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[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)[11]
- May have space to add another wide field instrument at DNIRI location

[10] Subsequent analysis (KAON 504) has led to an unvigneted technical FoV for LOWFS patrol of 180 arcsec diameter.

[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?[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.

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[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.

Architecture #	1	2	3	4	5
Name	Split Relay	Adaptive Secondary	Large Relay	Keck I Upgrade	Cascaded Relay
Description	dNIRI at focus + 30" dia relay	ASM feeds all instruments	Large relay for all instruments	Upgrade Keck I LGS AO system	Large relay + 30" relay for non-dNIRI instruments
Overall Ranking	2	5	4	3	1
Technical Ranking	3	5	4	2	1
Programmatic Ranking	1	5	4	3	2
Nasmyth AO size	Small	Small	Large (could be smaller with fewer actuator DM - performance impact)	Medium (current AO bench)	Medium
Rotation	dNIRI rotates, K-mirror in relay	Instrument rotates	K-mirror	K-mirror	K-mirror
HOWFS locn	In El journal	In El journal	After relay	After relay	After 1st relay
LOWFS locn	On or near dNIRI	On or near dNIRI	After relay	After relay	After 1st relay
dNIRI location	Uplooking at tel focus	Uplooking at tel focus	At AO focus	At AO focus	After 1st relay
NIR instrum	After relay	At tel focus	After relay	Two existing ports	After 2nd relay
Vis instrum	After relay	At tel focus	After relay	New vis arm port or existing ports	After 2nd relay
Interferometer	Doesn't meet needs	Doesn't meet needs	Potentially suitable	Already works	Potentially suitable after 1st relay
DM	64x64 MEMS for narrow field in K-mirror	35 act across (18 rings on ASM)	64x64 on PZT DM	20x20 PZT DM upgrade easy + 64x64 MEMS in narrow field science path	20x20+F34 PZT DM in 1st relay + 64x64 in narrow field science relay
LOWFS field dia (")	180" achievable	180" achievable	180" achievable	120" now; 180" possible with annular mirror	180" achievable
TTM locn	with DM	ASM	6 km conjugate?	Before relay	In 1st relay?
TT control	Open loop	Closed loop	Closed loop	Closed loop	Closed loop for 1st relay
HOWFS	Require large dynamic range or MEMS				
HO control	Open loop	Closed loop	Closed loop	Closed loop (for 1st DM)	Closed loop for 1st DM
LOWFS calibrations	Most non-common control between LOWFS & non-dNIRI instruments	Non-common path control	Least non-common path control	Least non-common path control (non-common path if 2nd relay)	Non-common path control
# of AO surfaces to NIR instrum	12	3-4	9-10	9-10	13
Achieving background	dNIRI at focus, AO relay cooled to ~ -14C	At tel focus	Cooled to ~ -10C	Cooled to ~ -10C	Cooled to ~ -15C
NIR PSF estim	Common PSF within 30" only	Big field available	120" field available	120" field available	Partially common-path PSF thru big relay; fully common-path within 30" only
DNIRI perf					
Narrow field performance					
Astrometry					
High contrast	Dichroic near focus disadvantage	Dichroic near focus disadvantage	K-mirror advantage	K-mirror advantage; K-mirror near focus disadvantage	K-mirror advantage
Δ Cost	+ $4.5M	+ $25.3M	+ $5.6M	0	+ $3.0M
Δ Cost w/ KI	+ $8.5M	+ $29.3M	+ $8.6M	0	+ $6.0M
Δ Ops Costs					
Risks	Tight fit to journal; all open loop	Tight fit to journal unless push focus; large ASM not demonstrated	Fit onto platform; large TTM	Operational system; 3.5 mm act spacing; cooling of existing components	Fit onto platform?
Add'l pros		Can benefit other foci/instruments	MCAO option	Early science return	Design & implementation flexibility
		GLAO in future		Graceful fallback	Graceful fallback
		Better for L&M-band			
		Can push focus to make more space; but then not useful for other instruments	Least instrument packaging constraints	Upgrades as funds available	Least instrument packaging constraints
Add'l cons	Keeping top surface clean	Keeping top surface clean	Full lab demo more difficult	Many existing constraints	
		To achieve performance tightened up multiple error terms (not reflected in costing)	Most difficult thermo-mechanical design and turbulence	Component obsolescence & reliability	
		All or nothing		Impact on AO ops	
Comment	New passive secondary or spherical corrector for pushing out focus			Could use a 40x40 DM	Could use a 40x40 DM
Technical Ranking Criteria:					
Performance Margin	Good	Fair-Good	Good	Good	Good
Operations Cost	Good	Fair	Fair	Fair	Good
Development Cost	3	5	4	1	2
Cost Risk	Medium	High	Medium-High	Low-High	Low
Technical Risk	High	High	Medium	Medium	Medium
Reliability	Good	Fair	Good	Fair-Good	Good
Interfaces	Poor	Poor	Poor	Good	Good
System Expandability	Good	Good	Fair	Poor	Good
Phasing compatability	Good	Poor	Poor	Very Good	Fair
Schedule Risk	?	High	?	?	?
Programmatic Ranking Criteria:					
Match to Strategic Goals	Excellent	Excellent	Excellent	Excellent	Excellent
Early Science/Phasing Flexibility	Good	Poor	Fair	Very Good	Good
Facilitation of Pre-Telescope I&T	Good	Poor	Fair	Poor-Fair	Good
Implementation Impact on AO Ops during development	Low	Low	Low	High	Low
Development Tied to Observing Schedule	No	No	No	Yes	No
dNIRI only AO costs	Good	Poor	Poor	Fair-Good	Fair
Community experience	Fair-Good	Poor	Fair-Good	Fair-Good	Fair-Good

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[13]. 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

Candidate Architecture	Question / Issue	Subsequent Result
All	Need accurate surface counts to evaluate transmission and emissivity challenges	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.
Split Relay	Need model to determine if split relay option fits (due to El bearing interference)	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).
	Can LOWFS achieve req'd tip/tilt error on sci instruments (given the apparently significant non-common path features (tip/tilt mirrors, rotators, ADC)	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).
	Could MEMS be significantly more or less expensive than assumed in our differtial cost comparison	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)
Adaptive Secondary Mirror	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.)	Not subsequently considered due to lack of time.
Large Relay	Confirm large DM costs	D. Gavel contacted Xinetics and CILAS with inqueries. CILAS responded with a ROM quote that was somewhat, but not significantly, higher than our internal estimate (see D. Gavel for details, if interested.)
	Can the optical design meet the needs of Keck Interferometer?	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)
Keck 1 Upgrade Path	What is the minimum technical field of view required for LOWFS NGS?	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.

[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.

	Need a 'convincing' upgrade plan (that would not suffer from significant loss of AO observing time)	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.
	Need more careful analysis of re-engineering costs, including review by the Keck AO team and Sean Adkins	To be addressed in subsequent cost estimation by D. Gavel.
Cascaded Relay	Need a feasible optical design and packaging concept	B. Bauman produced a conceptual optical design (using Zemax) that to first order met the configuration requirements with acceptable optical performance (to be documented in an upcoming KAON with D. Gavel).
	Can the optical design meet the needs of Keck Interferometer?	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.)
	Surface counts / Transmission	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).

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

Architecture	Tel.	N.F. AO	W.F. AO	K Mirror	Na Dichroic	DNIRI Pickoff	ADC	2nd TT	Ent. Win.	Sci. Fold	Total
Split Relay	3	3+4[⊕]	-	2[*]	2	2	6	-	4	1	27
ASM	3	-	-	-[°]	2	2	6	-	-	1	14
Large Relay	3	-	3+1[†]	3	2	2	6	1	4	1	26
K1 Upgrade	3	3	4[‡]	3	2	2	6	1	4	1	29
Cascaded Relay	3	3+4[⊕]	3	3	2	2	6	-	4	1	31

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, [⊕] - 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

Architecture	Tel.	N.F. AO	W.F. AO	K Mirror	Na Dichroic	DNIRI Pickoff	ADC	2nd TT	Ent. Win.	Sci. Fold	Total
Split Relay	3	-	-	-[°]	-	1	-	-	4	-	8
ASM	3	-	-	-[°]	-	1	-	-	-	-	4
Large Relay	3	-	3+1[†]	3	-	1	-	1	4	-	16
K1 Upgrade	3	-	4[‡]	3	2	1	-	1	4	-	18
Cascaded Relay	3	-	3	3	-	1	-	-	4	-	14

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

Architecture	Tel.	N.F. AO	W.F. AO	K Mirror	Na Dichroic	DNIRI Pickoff	ADC	2nd TT	Ent. Win.	Sci. Fold	Total
Split Relay	3	-	-	-[°]	1	2	-	-	2[††]	-	8
ASM	3	-	-	-[°]	1	2	-	-	-	-	6
Large Relay	3	-	3+1[†]	3	1	-	-	1	4	-	16
K1 Upgrade	3	-	4[‡]	3	1	2	-	1	4	-	18
Cascaded Relay	3	-	3	3	1	2	-	-	4	-	16

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, [§] - 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:

Architecture	**Final Ranking**	**Notes**
Cascaded Relay	**#1**	**Adopted as NGAO Baseline Architecture** and will be carried forward through remainder of the NGAO System Design Phase.
Split Relay	#2	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
Keck 1 Upgrade	#3	Will be carried as an avenue for early NGAO program science return and as an NGAO alternative in the most pessimistic funding scenarios.
Large Relay	#4	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.
Adaptive Secondary Mirror	#5	Deemed too expensive and too technically risky to meet NGAO Science Requirements.

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

WBS Element Title:	NGAO System Architecture Definition
WBS Element Number:	3.1.3
Work Package Lead:	Richard Dekany
Work Package Participants:	Bauman, Gavel, Flicker, Neyman, Velur, Wizinowich

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 decisionsin 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: <u>May 24, 2007</u>

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

<u>May 30, 2007</u>

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

<u>Tuesday, June 5, 2007</u> (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)

<u>June 13, 2007</u> (Velur and Dekany traveling)

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

<u>June 20, 2007</u> – No Meeting (OSA conflict)

<u>June 27, 2007</u>

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)

3.1.3.1.1 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)
3.1.3.1.2 Subsystem Performance Evaluation = 72 hrs (3 x 12 x 2, Dekany, Gavel, Wizinowich)
3.1.3.1.3 Subsystem Cost Evaluation = 72 hr (3 x 12 x 2, Bauman, Neyman, Velur)
3.1.3.1.4 Subsystem Risk Analysis = 36 hr (3 x 12 x 1, Bauman, Neyman, Velur)
3.1.3.1.5 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

Functions		Subsystems	Telescope	Science instruments	AO enclosure	Field Rotation	Optical Relay	Optical switchyard	Optical support struc.	High order LGS WFS	High order NGS WFS	Low order NGS WFS	Calibration(truth) wavefront sensors	Tip Tilt correction	HO correction	Vibration mitigation	NGS acquisition	LGS acquisition	Atmospheric Dispersion Cor.	Metrology	Atmospheric profiler	Calibration Unit	PSF montoring camera	RTC hardware and software	Sequencer for observing, setup & calibration (Software)	Laser (or lasers)	Laser launch facility	Laser poiinting and diagnostics (hardware & software)	Laser Launch telescope	Laser safety (personel, airtraffic, obs. collision)	Science observing simulation	AO guide star selection	AO realtime optimation (optimizer)	Observing Tools
Configure	Power on/off		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Record NGAO status																							x	x			x		x			x	
	Configure calibration source						x	x														x			x									
	Configure pupil sampling						x	x		x	x	x	x												x									
	Configure Science transmissions			x			x	x																	x									
	Configure HO WFS transmissions						x	x		x	x														x									
	Configure HO WFS camera settings																							x	x									
	Configure HO WFS servo Lloops																								x									
	Configure HO WFS reconstructor																							x	x									
	Configure TT WFS transmissions						x	x				x													x									
	Configure TT WFS camera settings																							x	x									
	Configure TT WFS servo loops																							x	x									
	Configure Truth WFS transmissions						x	x					x												x									
	Configure Truth WFS camera settings																							x	x									
	Configure Truth WFS servo loops																							x	x									
Produce LGS	Configure laser(s)																									x	x	x	x	x				
	Check laser status																											x						
	Check laser beam train status																										x	x						
	Check air traffic																													x				
	Check US space command																													x				
	Check telescope collisions																													x				
	Propagate laser																									x	x	x	x	x				
	Align laser to HO wfs																										x	x						
	Control laser pointing																											x						
	Control laser polarization																									x		x						
	Control laser power																									x		x						
	Correct up-link HO wavefront																										x	x						
	Correct up-link tip tilt																										x	x						
Acquire	Acquire Science Target(s)		x	x																					x									
	Acquire NGS Mode: TT Star(s)		x									x					x								x							x		
	Acquire NGS Mode: LOWF Star(s)		x									x					x								x							x		
	Acquire NGS Mode: HO Star(s)		x								x						x								x							x		
	Acquire NGS Mode: HO Truth Stars		x										x				x								x							x		
	Acquire NGS Mode: Calibration Source(s)												x												x									
	Acquire LGS Mode: Project Lasers																									x	x	x	x	x				
	Acquire LGS Mode: Compensate Uplink																										x	x						
	Acquire LGS Mode: TT Star(s)		x									x					x								x							x		
	Acquire LGS Mode: Null Mode WFS Star(s)		x									x					x								x							x		
	Acquire LGS Mode: HO WFS LGS		x							x								x							x									
	Acquire LGS Mode: Truth WFS NGS		x										x				x								x									
Sense Wavefronts	Sense NGS TT/LO Wavefront											x												x										
	Sense NGS HO Wavefront										x													x										
	Sense NGS Truth Wavefront												x											x										
	Sense LGS TT Wavefront											x												x										
	Sense LGS LOWF (Null Modes)											x												x										
	Sense LGS HO wavefront									x														x										
	Sense LGS truth Wavefront												x											x										
Synthesize Wavefront Correction	Synthesize Science Wavefront(s)																							x										
	Synthesize NGS Wavefronts (Non Science)																							x										
	Synthesize LGS Wavefronts (Non Science)																							x										
Compensate Wavefronts	Compensate Tip/Tilt													x																				
	Compensate HO Wavefronts														x																			
	Compensate Atmospheric Refraction																		x															
	Compensate Field Rotation					x																												
	Offload HO Wavefront		x							x	x				x									x	x									
	Offload LO Wavefront		x									x		x	x									x	x									
	Offload TT Wavefront		x									x		x																				
	Apply Static HO Corrections														x									x	x									
	Apply Static Tip/Tilt Corrections													x										x	x									
Self Test & Diagnostics	Align Optical Relay						x			x	x	x	x	x	x							x												
	Align WFS's						x			x	x	x	x	x	x							x												
	Register DM's to One Another									x	x	x	x		x							x												
	Register DM's to WFS's									x	x	x	x		x							x												
	Check Vignetting			x			x			x	x	x	x	x	x							x												
	Record AO Telemetry																							x									x	
	Calculate Performance Metrics																				x			x									x	
Calibrate	Calibrate WFS's									x	x	x		x	x							x												
	Calibrate DM's									x	x	x		x	x							x												
	Dither Laser Wavelength																									x		x						
	Measure Cn2(h,t)																				x													
	Generate Reconstructors																							x							x		x	
Safety	System Safety																									x	x	x	x	x	x			
	Human Safety																									x	x	x	x	x	x			
Science	Plan observation																														x			x
	Relay Science Light			x			x																											
	Dither Science Light			x			x			x	x	x				x	x	x							x									
	Chop Science Light			x			x			x	x	x				x	x	x							x									
	Calibrate observation																					x	x	x	x								x	x
	Perform Observation			x																														
	Optimze AO performance																							x									x	
	Report Performance to Operator/Observer																							x	x								x	x
	Record Observation			x																														x
	Reduce Science and Calibration Data																																	x
	Archive Data																																	x

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.

Evaluation Criteria	**Definition**
Performance Margin	Does this option meet the performance requirements and how much margin is there?
Operations Cost	Will this lead to low operations costs (procurement dollars and operations personnel costs)? This should include maintainability.
Development Cost	What are the relative development costs (dollars)?
Cost Risk	Is the risk to the development or operation costs low?
Technical Risk	Is the risk to not meeting the performance requirements low?
Reliability	Is the reliability of this option high? In particular, with respect to up-time of the system.
Interfaces	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.)?
System Expandability	Is this option easily scalable and does it offer future capabilities?
Upgrade Applicability	Can this option be implemented on the current Keck AO systems? Consider the downtime to implement these upgrades in the evaluation.
Rankings =	Poor, fair, good & excellent.
Cost Evaluation	
Cost Estimate (1st unit)	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.
Cost Uncertainty	It is adequate to have this at the +/- 50 or 100% level initially.
Unit Cost (2nd to nth unit)	ROM to build each subsequent unit.
Basis for Estimate	Any key information or assumptions used in estimating the costs.

Table 6. Subsystem and Architecture Technical and Differential Cost Evaluation Criteria.

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:

Programmatic Evaluation Criterion	**Definition**[15]
Match to Strategic Goals	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"
Early Science / Phasing Flexibility	How well does this architecture enable early science results that are unique and only possible using NGAO developments? How well does this architecture absorb uncertainities in the funding profile to enable a phased implementation of the full NGAO capability?
Facilitation of Pre-Telescope I&T	How well does this architecture support integration and testing at the development site, prior to shipment to the summit?
Implementation Impact on AO Operations during development	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.?
Development Tied to Observing Schedule	To what extent would the NGAO Project Plan be constrained by needing to fit into (or in between) on-going observing schedule constraints?
dNIRI only AO Costs	To what extent does this architecture allow for top-priority development of the DNIRI instrument, if total program funding is severely constrained?
Community Experience	Does the Keck instrumentation community have related experience, by specifically having demonstrated this architecture or key elements thereof?

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

Function	Method	Performance Margin	Development Cost	Operations Cost	Cost Risk	Technical Risk	Reliability	Interfaces	System Expandability	Upgrade Applicability
Correct High-Order										
	Adaptive Secondary	(1)	Very Bad	Bad	Very Bad	Very Bad	Unknown		Very bad	Good
	Piezo DM	(1)	Moderate	Moderate	High	Moderate	Good		Bad	Possible
	MEMS DM	(1)	Good to Bad (2)	Unknown	Low	Moderate	Unknown		Very good	Low

(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

Function	Method	Performance Margin	Development Cost	Operations Cost	Cost Risk	Technical Risk	Reliability	Interfaces	System Expandability	Upgrade Applicability
Correct Tip-Tilt										
	Chopping / adaptive secondary	Bad (3)	Very Bad						Bad	Good
	DM on tip/tilt stage	Bad (3)	Very Bad		Bad	Bad			Bad	Probably not
	mirror	Moderate (3)	Good		Good	Good			Good	Good

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

Function	Method	Performance Margin	Development Cost	Operations Cost	Cost Risk	Technical Risk	Reliability	Interfaces	System Expandability	Upgrade Applicability
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	Unknown		Good	Good

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

Function	Method	Performance Margin	Development Cost	Operations Cost	Cost Risk	Technical Risk	Reliability	Interfaces	System Expandability	Upgrade Applicability
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 deminishing returns

Function	Method	Performance Margin	Development Cost	Operations Cost	Cost Risk	Technical Risk	Reliability	Interfaces	System Expandability	Upgrade Applicability
Project Lasers: Beam Projector										
	Variable asterism	Good (6)	Bad, potentially	Unknown	Bad, potentially	Moderate	Bad		Bad, potentia	Compatible
	Fixed set of asterisms	Bad	Acceptable	Acceptable	Acceptable	Acceptable	Good		Moderate	Compatible
	Single launch telescope with shared aperture	(7)	Good	Good	Good	Good	Good		Good	Compatible
	Multiple launch telescopes	(7)	Good	Bad	Good	Good	Good		Bad, depends	Compatible

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

Keck Next Generation Adaptive Optics
Sub-system assessment, by functionality and implementation method
Anna Moore

Subsystem Function =	Tip-Tilt star pick-off			
Option = Description	**Optical switchyard**	**Fishing rod**	**Tiled focal plane**	**Kickbot**
Evaluation Criteria				
Performance Margin	Unsure	Very good	Very good/Excellent	Excellent
Operations Cost	Excellent	Very good	Very good	Very good
Development Cost	Good/Fair	Fair/good	Fair/good	Very good
Cost Risk	Excellent	Good	Fair	Fair
Technical Risk	Very good/Excellent	Good/very good	Good	Good
Reliability	Excellent	Very good	Good	Good
Interfaces	Very good	Good	Good	Very good
System Expandability	Fair/Good	Very good	Good	Very good
Upgrade Applicability	Excellent	Good	Fair	Good
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	Prototype exists but would need to be fully developed for this application	Prototypes exist but would need developing for this application

Subsystem Function =	On chip dithering			
Option = Description	**Optical switchyard**	**Fishing rod**	**Tiled Focal Plane**	**Kickbots**
Evaluation Criteria				
Performance Margin	Excellent	Good	Excellent	Excellent
Operations Cost	Excellent	Excellent	Excellent	Excellent
Development Cost	Very good	Good/Fair	Fair	Fair
Cost Risk	Very good	Good	Good	Good
Technical Risk	Very good	Good	Good/Fair	Good/Fair
Reliability	Very good	Very good	Very good	Very good
Interfaces				
System Expandability	Excellent	Fair/Good	Very good	Excellent
Upgrade Applicability				
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

Brian Bauman

Function	Method	Performance Margin			Development Cost	Operations Cost	Cost Risk	Technical Risk	Reliability	Interfaces	System Expandability	Upgrade Applicability
		throughput	imaging	pupils								
Optical relays	Reflective	very good	good for field size < pupil size	good for field size < pupil size	low, unless using very large DM's (larger space requirements)	low	moderate	low	high	needs output format defined	limited to field=pupil diameter	limited to field=pupil diameter
	Refractive	good (falls off at K)	good for field size < 2 * pupil size	good for field size < 2 * pupil size	low, unless using very large DM's (larger space requirements)	low	moderate	moderate	high	needs output format defined	limited to field=2*pupil diameter	limited to field=2*pupil diameter
LGS WFS	split off via dichroic in front	very good	very good	very good	moderate (1)	moderate	moderate	moderate	moderate	good	good	good
	picked off after relay	very good, but could be limitations in field	could suffer if field is much larger than pupil size	could suffer if field is much larger than pupil size	moderate (1)	moderate	moderate	moderate	moderate	good	fair	fair
LOWFS	via pickoffs at front	very good	very good	very good	moderate (1)	moderate	moderate	moderate	moderate	good	good	good
	picked off after relay	very good	could suffer if field is much larger than pupil size	could suffer if field is much larger than pupil size	moderate (1)	moderate	moderate	moderate	moderate	good	fair	fair

(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

Candidate	Array of Na beacons, reconfigurable between narrow and wide LGS asterisms, with independent patrolling d-IFU's	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	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
Evaluation Criteria			
Performance Margin	Fair	Good (TBC)	TBD
Operations Cost	Fair	Fair	Excellent (TBC)
Development Cost	Poor	Poor	Good
Cost Risk	Fair	Fair	Good
Technical Risk	Fair	Fair	TBD
Reliability	Fair	Fair	Good
Interfaces	Good	Good	Good
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 chosing an appropriate laser architecture.

Keck Next Generation Adaptive Optics
Sub-system assessment, by functionality and implementation method
Chris Neyman

Subsystem Function = LGS mode low order wave front sensor

Candidate	2 IR Trackers + 1 TTFA IR-Pyramid	2 IR Trackers + 1 TTFA IR SH	2 APD Tracker + 1 TTFA Shack Hartmann (CCD)	2 APD Tracker + 1 TTFA Pyramid (CCD)
Evaluation Criteria				
Performance Margin	good	fair	poor(good see comments)	poor (good see comments)
Operations Cost	good	good	good	good
Development Cost	fair	fair	good	good
Cost Risk	fair (poor)	fair (poor)	good(fair see comment)	good(fair see comment)
Technical Risk	fair (poor)	fair (poor)	good	good
Reliability	good	good	good	good
Interfaces	fair	fair	good	good
System Expandability	good	good	good	good
Upgrade Applicability	fair (poor)	fair (poor)	fair	fair
final ranking	1	2	3	4

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

Subsystem Function = NGS mode Tip Tilt Wave front sensor

Candidate	Shack-Hartmann WFS (CCD)	IR Tracker	APD Tracker
Evaluation Criteria			
Performance Margin	good	good	good
Operations Cost	good	good	good
Development Cost	good	fair	good
Cost Risk	good	fair (poor)	good(fair see comment)
Technical Risk	good	fair (poor)	good(fair see comment)
Reliability	good	good	good
Interfaces	good	fair	good
System Expandability	fair	fair	
Upgrade Applicability	fair	fair (poor)	
Additional Criteria/Notes		Might benefit from dedicated tracker	Might benefit from dedicated tracker

Subsystem Function = LGS mode Truth Sensor

Candidate	SH-WFS	Large FOV imaging detector	small FOV imaging detector
Evaluation Criteria			
Performance Margin	good	good	good
Operations Cost	good	good	good
Development Cost	good	fair	fair
Cost Risk	good	fair	good
Technical Risk	good/excellent	good	good
Reliability	good	good	good
Interfaces	good	fair	fair
System Expandability	fair	fair	fair
Upgrade Applicability	fair	fair	fair
Additional Criteria/Notes	single head movable around field of regard might be on instrument wavefront sensor	Use in focus and out of focus images, along with phase diversity algorithms to recover performance might be science camera might be PSF monitor camera	Use in focus and out of focus images, along with phase diversity algorithms to recover performance might be science camera might be PSF monitor camera

Appendix 3. System Architecture Retreat Agenda

Keck NGAO Team Meeting #8

9:00 a – 6:00 p (Pacific Daylight Time)

Mon, July 9 to Fri, July 13, 2007

Center for Adaptive Optics, UC Santa Cruz

Telecon attendees: 877-280-4645 passcode 540030 Videoconference IP: 128.114.22.14

Keck conference rooms

Monday: Hualalai (IP#128.171.99.70, 881-3534 console, 881-3522 backup)
Tues: Mauna Kea (IP#128.171.99.74, 881-3890 console, 881-3806 backup)
Wed-Fri: Kamuela (IP#128.171.99.69, 881-3533 console, 881-3505 backup)

Directions: CfAO web site (.html) and Directions to the Center (.html)

In propria persona (full week):	Bauman, Dekany, Gavel, Max, Moore, Neyman, Velur, Wizinowich					
In propria persona (partial week):	Le Mignant (Mon & Tues), McGrath (Mon - Wed, Thur/Fri TBC)					
In effigie (e.g. on the phone – partial week (all TBC...?)):	Adkins (Mon pm Requirements summaries, Thurs pm Design choices & FRD or Program structure)	Bouchez (TBD)	Britton (Mon am Requirements summaries)	Chin (Tues & Wed Reports, Thurs am Architecture ranking, Thurs pm Design choices & FRD)	Johansson (Mon Summaries, Tues & Wed Reports, Thurs am Architecture ranking, Thurs pm Design choices & FRD)	

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

Minutes:

Claire's notes MondayNotes.txt TuesdayNotes.txt WednesdayNotes.txt ThursNotes.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(SCRD & SRD).

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 ROM development cost estimate & subjective operations cost estimate

Candidate Architectures

-
    - #1 SplitRelay – Split 20" Narrow field instruments / 120" d-NIRI relay architecture
    - #2 AM2 – Adaptive secondary mirror architecture(s)
    - #3 LargeRelay – Single 180" TFoV relay architecture working session
    - #4 KI Upgrades – Keck I upgrade path architecture
    - #5 CascadedRelay – A variant of LargeRelay in which a 2nd stage is used for narrow-field instruments, reducing 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**)tradestudysummary.ppt

- 12:00 pm Lunch
- 1:00 pm Summarize/review science requirements impacting AO architecture – review summary tables (**Max**) * 070709_NGAO_RollUp_v1.xls * 070709_NGAO_Inst_Suite_v1.xls * 070709_Max_SciReqs.ppt: 070709_Max_SciReqs.ppt
- 1:55 pm Summarize/review science operations requirements impacting AO architecture (**Le Mignant**)
- 2:05 pm Summarize/review system requirements impacting AO architecture (**Wizinowich**)
- 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 Mignant, McGrath, Moore, Velur, Wizinowich**)
- 3:30 pm Working session #2 – Adaptive secondary mirror architecture (**Proposed: Dekany, Gavel, Max, Neyman**) KAON485 ASM Trade Study ASM Schematic
- 6:00 pm Adjourn

Tues, July 10 <-- 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 30" Narrow field instruments / 120" d-NIRI relay
- 8:00 am Working session #2 (cont) – Adaptive secondary mirror
- 10:30 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, Velur**)
- 12:30 pm Working session #4 – Keck I upgrades architecture working session (**Proposed: Bauman, Gavel, Max, Wizinowich**) KAON461 Upgraded Keck AO Performance KAON462 Keck AO Upgrade Trade Study Keck AO Schematics
    - 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 I upgrades architecture (**All**)
- 6:30 pm Dinner at CfAO

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

- 8:00 am Brainstorming Session (**All**)
- 9:00 am Brainstorm Architecture #5 (**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 am Report #5 – Architecture #5 (**All**)
- 3:30 am Report #6 – Architecture #6 (**All**)
- 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 12 <--- 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**) FRD v0.1
- 2:30 pm FRD Development working session
    - AO system architectural assumptions (Neyman)
    - Laser system architectural assumptions (Velur)
    - AO system optical requirements (Neyman to define participants)
    - Laser system optical requirements (Velur 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**) (TBC)
- 5:30 pm Program Structure Report and Discussion (**All**)
- 6:15 pm FRD Issues Discussion (**All**)
- 7:00 pm Dinner at CfAO

Fri, July 13 <-- 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 Architectures Options Summary (**Moore, McGrath**)
- 10:45 am Functional Requirements Document Overview (**Wizinowich**) FRD v0.1
- 11:30 am FRD Development working session
    - AO system architectural assumptions (Neyman)
    - Laser system architectural assumptions (Velur)
    - AO system optical requirements (Neyman to define participants)
    - Laser system optical requirements (Velur 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 (**All**)
- 3:00 pm FRD Issues Discussion (**All**) * FRD_outline.doc:
- 3:30 pm Action Items & Schedule Summary (**All**)
- 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
History: r50 - 13 Jul 2007 - 23:24 - PeterWizinowich

Appendix 4. Original System Architecture Retreat (Team Meeting #8) Schematics

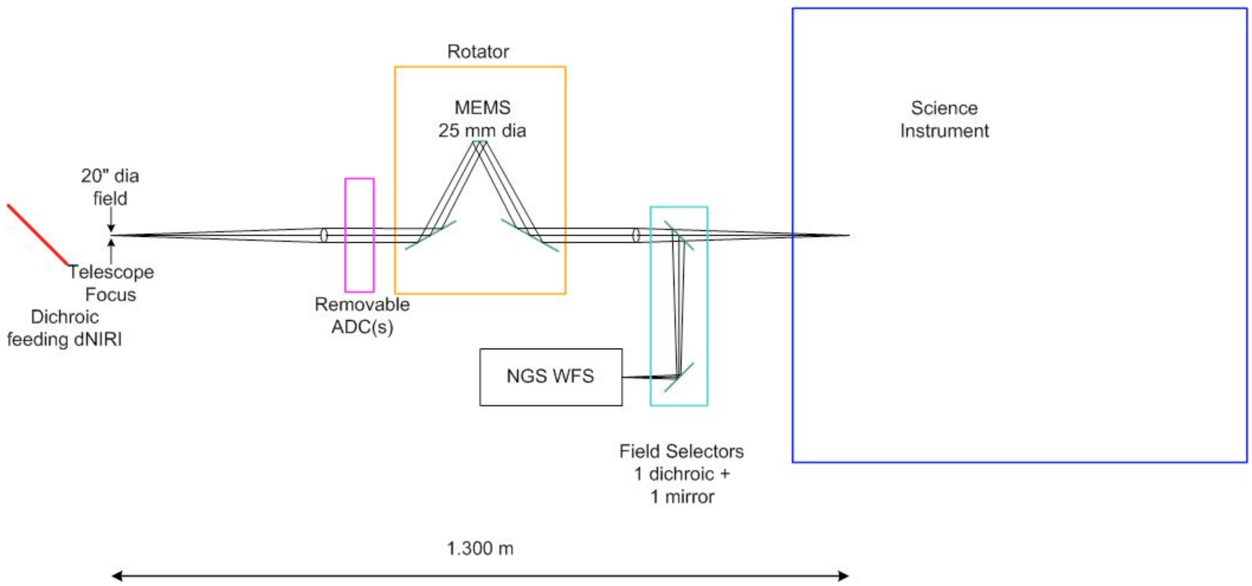

Figure 7: Original schematic of the "Split Relay" system architecture generated 7/9/07.

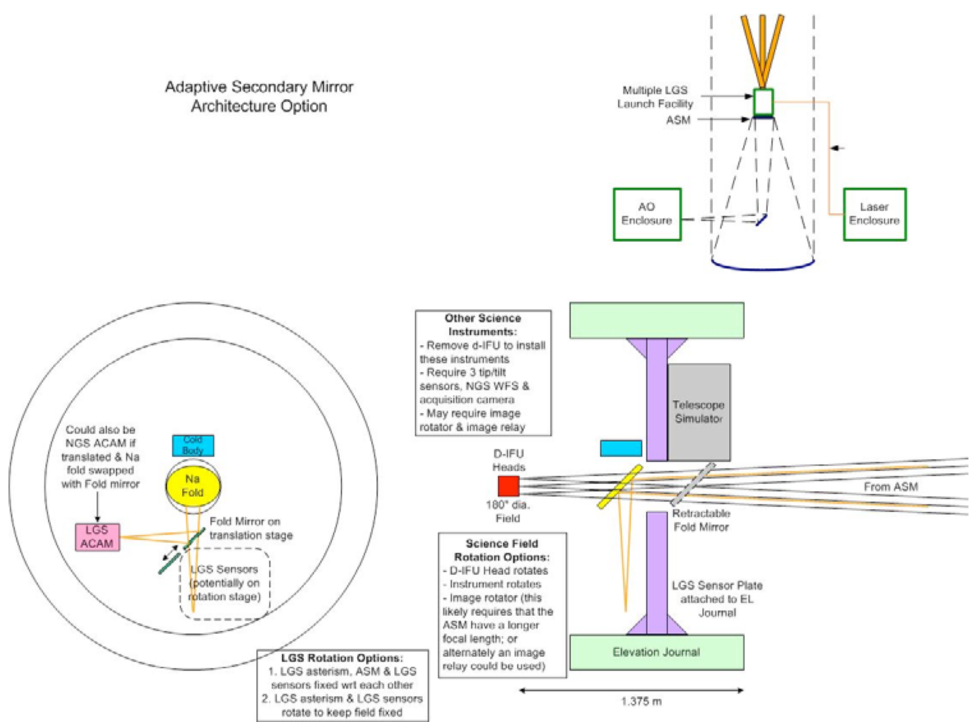

Figure 8. P. Wizinowich's original schematic layout for the Adaptive Secondary architecture

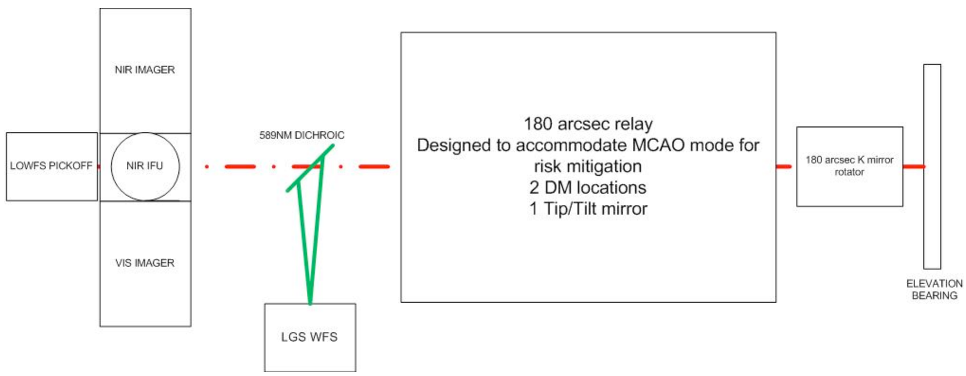

Figure 9. Original schematic of the "Large Relay" System Architecture. (Reference also the June 2006 NGAO proposal which also presented a feasibly optical layout and packaging design fitting the relay and 3 simultaneously mounted instruments on the Nasmyth platform.)

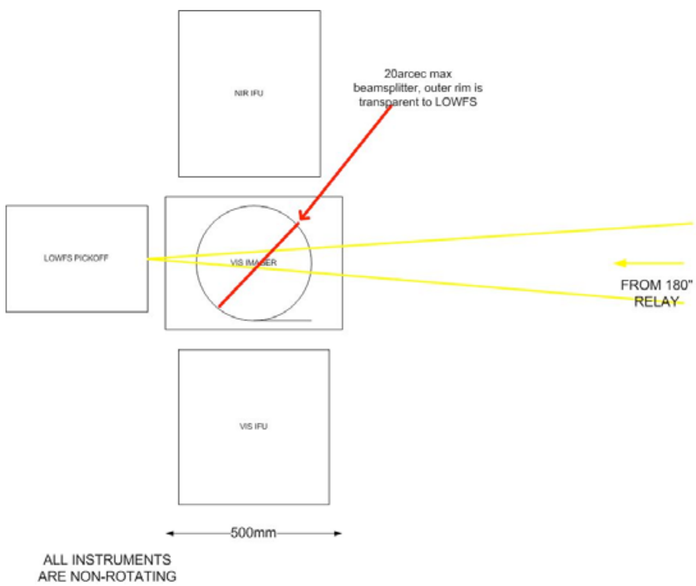

Figure 10. A. Moore’s original “LEGO block” configuration schematic for instruments fed by the Large Relay. Note, DNIRI is missing from this diagram, but could be fed as an instrument ahead of the ‘lego stack’ (e.g. off to the right), or as an instrument ‘behind’ the Vis Imager shown (potentially excluding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

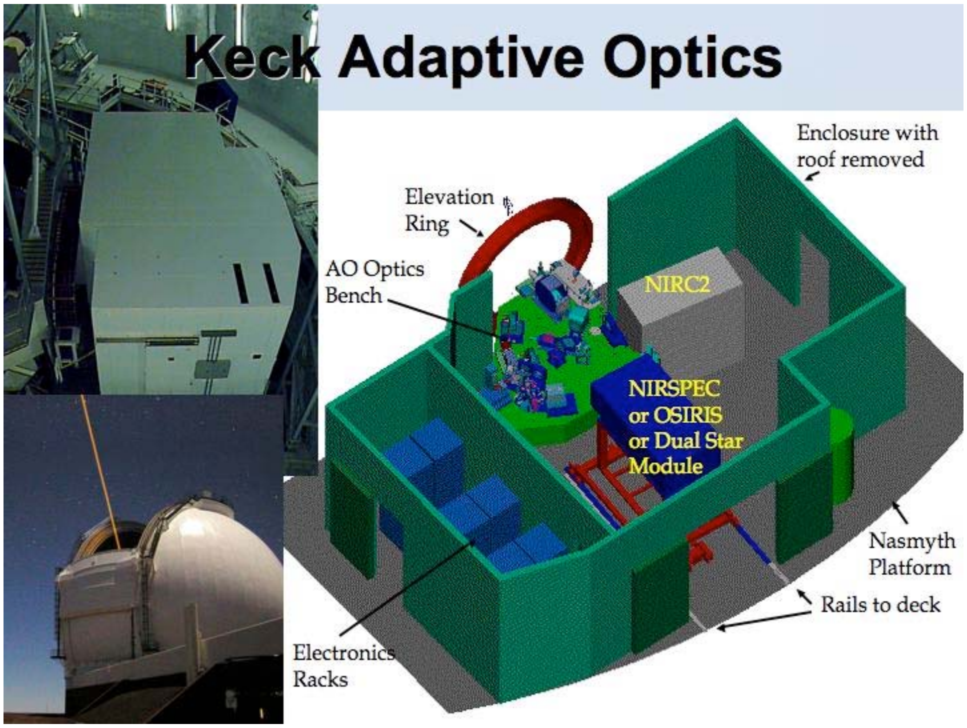

Figure 11. A reference depiction of the current Keck Adaptive Optics system used for discussion of the Keck 1 Upgrade Path architecture.