Keck NGAO Trade Study: Keck Interferometer Support

KECK ADAPTIVE OPTICS NOTE 483

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March 31, 2007

ABSTRACT

This report discusses several options for supporting observation with the Keck Interferometer when NGAO is installed on the telescope. These options are driven by the need to match the electric field orientation and S-P polarization phase shift between telescopes so that high contrast interference fringes result. No totally satisfactory option was found that is both low cost and provides satisfactory performance. Recommendations are given in the last section.

1. Introduction

The direction and scope of this trade study was formulated as part of the NGAO system design management plan [1]. As part of the planning for this study, the scope of the trade study was modified [2]. The scope of this trade study is:

> Consider the relative performance, cost, risk and schedule of feeding KI with NGAO or a repackaged version of the current AO system. Decoupling of NGAO from interferometer support may simplify and improve performance of NGAO. The feasibility of maintaining a version of the two current AO systems for KI use should be evaluated. Complete when NGAO baseline architecture selected.

This study will define the constraints and requirements for supporting interferometry at Keck in the NGAO era (~2013). Several possible concepts for interferometer support will be evaluated. The final architecture decisions for NGAO in this phase of the project will be made as part of W.B.S. 3.1.3.1: System Architecture. This study will be used to guide those decisions. The methodology of this study will be to use mechanical and optical design tools to develop concepts for supporting interferometery. Given the hours allocated to this study, the designs can only be taken to a conceptual level. The requirements and constraints for interferometry support at Keck will be taken from:

> "Issues related to the Location of the Keck I Adaptive Optics Bench" KAON 165 [3]
> "Implication and Requirements for Interferometry with the Next Generation Adaptive Optics System" KAON 428 [4]

Optical designs used to evaluate compatibility between NGAO and interferometry will be taken from W.B.S. 3.1.2.2.2: Optical Relay. As this optical design study is only partially complete at this time, updates will be made as information is available. The rest of the study presents issues and design concepts for three options for support of the interferometer

2. Conceptual Design for IF Support

2.1. NGAO Feeding One Interferometer Arm

If NGAO will feed one arm of the Keck Interferometer, while the other is fed from a current AO system, then NGAO must match the current Keck AO systems in a number of aspects. Although matching Strehl is a consideration, because of the design of the KI fringe tracker, simply matching the average intensity coupled into each arm of the fringe tracker can solve this problem, see a more complete discussion in KAON 428 [4]. The more unforgiving requirement is the need to match the electromagnetic field orientation and polarizations from each telescope. In order to achieve interference between the two telescopes, the electromagnetic field from each telescope must be in the same spatial orientation and relative phase lags between orthogonal polarization states (i.e. S and P) must be the same in each arm before the beams are interfered. The current Keck Interferometer (KI) achieves electric field matching by keeping the number, ordering, and angle of all the reflections the same in both beam trains from each telescope. It is especially important to keep the polarization phase shift from non-normal reflections from metallic coatings in the correct order, see Figure 1.

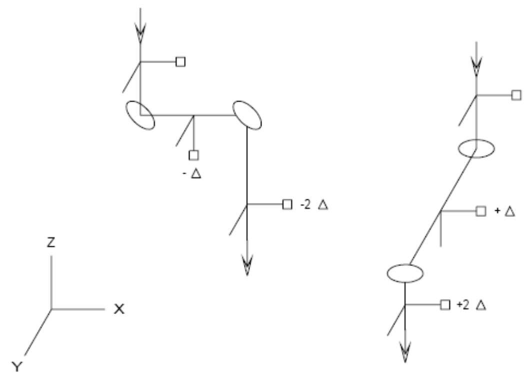

Figure 1: Illustration of importance of matching reflections, although the final electric fields have the same orientations, the polarization undergo different relative phase shifts.

The AO systems currently on Keck I and Keck II have identical optical designs and coatings. For a generic interferometer, as the beams are brought from the telescopes to the beam combiner, extra reflections are added in some places to the beam train to maintain the matching electric fields, see Figure 2, beam train C. This design methodology, suggested by Traub [5], is standard practice in the stellar interferometry field. However, other options may be implemented for interferometry with NGAO. The differential s-p phase shift in the current Keck Interferometer is estimated at 6 degrees resulting in a loss in visibility squared, V^2, of 0.003. This needs to be maintained for all science wavelengths that the interferometer uses for fringe tracking and nulling. Note also that the rotation match requirement is absolute - no mirror flip differences allowed which is implicit in the values given for current KI assuming two completely symmetric arms (one from each telescope) with only alignment and manufacturing tolerances. If a major asymmetry is added to the system, there may be additional requirements levied, particularly for nulling as the fringe symmetry may change with an asymmetrical beam train.

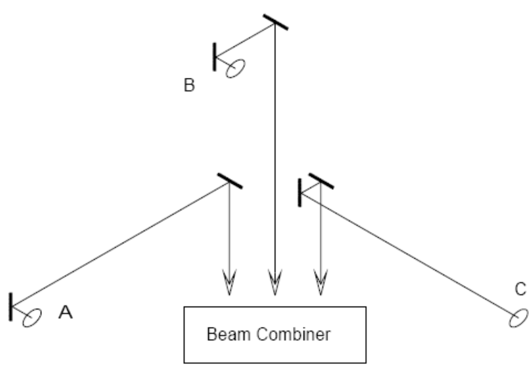

Figure 2: Standard methodology requires the same orientation and order of reflections in each beam train.

Matching polarization in interferometry is a difficult problem. As mentioned above, the best approach to mitigating the problem is to use identical optical trains. For the case of NGAO, one can envision a pair of periscope mirrors that maintains the phase of the S and P polarization of the input beam [6]. The mirror pair is adjusted slightly in angle to introduce a compensating polarization shift. One advantage of this approach is that it is intrinsically broad band in application because is only uses reflective optics. Transmissive optical materials that modify polarization, such as calcite, tend to have high transmission only over a small part of the interferometers working band pass. The mirror pair approach will be easier to implement if both the legacy AO system and NGAO have reflective K mirror image rotators with identical coating this would make any temporal variation in polarization between the AO systems identical. An NGAO system with mechanical rotators would make the polarization matching problem harder. In addition building the NGAO main optical relay in one plane like the legacy systems would simplify the polarization matching problem. It may be useful to coat the legacy and NGAO relays with identical materials again making it easier to match the polarization. In order to proceed further with these ideas requires modeling the polarization of the NGAO optical relay in detail. This may prove to be a difficult undertaking in practice. The reason the problem becomes intractable in the case of optical systems with arms that are not identical is that the coatings are often not characterized as well as they should be or the vendor does not give out detailed information for the coatings, as it is proprietary. Even if all the information is available, optical design software can also provide its own pitfalls. For example, Zemax has been reported [7] to lose track of polarization phase wraps, i.e. when the total shift is larger than 2 pi.

An example of the difficulty in matching beam trains may be extracted from the following experience with the current system. In fall of 2003, the AO system image rotator (K mirror) was recoated on K1 but not K2, during the next interferometer run, the system visibility (V^2) dropped by about one half, after K2 was recoated the visibility returned to its normal value. The drop in visibility was assumed to be due to the differences in the protecting overcoat of the silver coating. Also the mirrors in the image rotator are at a 60-degree angle of incidence where polarization phase shifts are expected to be large.

A Martin-Puplett [8] polarization modulator is one way by to split the S and P polarizations and change their relative phases. More work is needed to see how large a wavelength range over which this works (the path difference and the equivalent phase difference are dependent on wavelength path difference) and how accurate a stage/optical set up is required. An alternative is a Soleil-Babinet [9] compensator that is formed by a fixed and a movable wedge that acts as a continuously variable wave plate. Again, this also works only over a finite wavelength range.

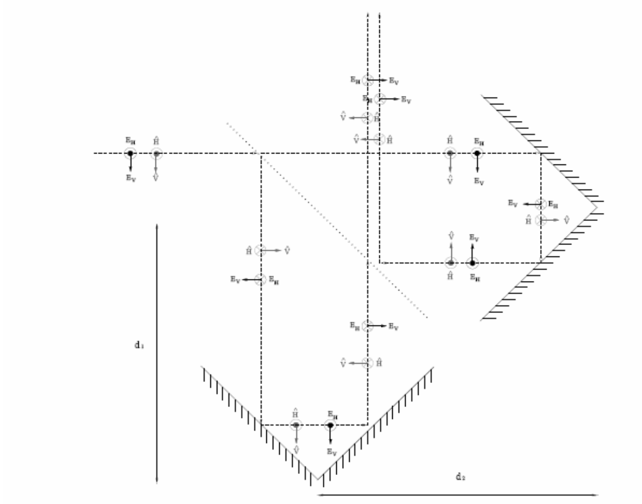

Figure 3: Diagram of Martin Puplett interferometer from reference [8]

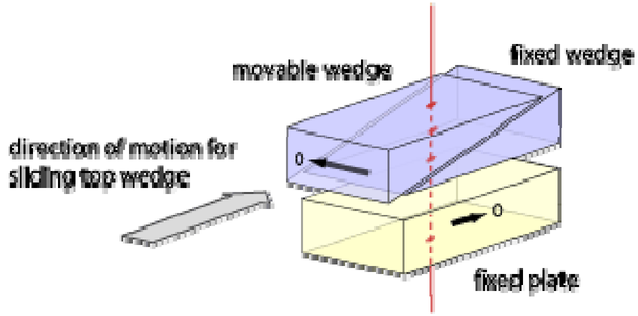

Figure 4: Diagram of Soleil-Babinet compensator from reference [9]

2.2. Dual IF Specialized AO Systems

Another option for interferometery with NGAO would be to have two identical AO systems that are dedicated to interferometer operations. These identical systems would by design have matching phase shifts and electric field orientations by virtue of their identical optical trains. This approach was taken by ESO for the VLTI. ESO constructed 4 identical bimorph mirror curvature AO systems for interferometery (and 2 others for single telescope AO instruments). These systems used standardized components and similar systems for Keck might be built by the University of Hawaii or ESO.

Another option would be the installation of adaptive secondary mirrors on each telescope. At present this approach appears expensive and has high technical risk. However, the AO secondary would provide a high transmission system with low thermal IR background. It might also be more attractive if the AO secondary were used in a dedicated thermal IR (3-5 μm) AO system or in ground layer system for future wide field instruments, allowing Keck's facility investment in AO to be utilized by the largest number of instruments, see NGAO ground layer trade study.

The prospect of building two new AO systems in addition to the cost of NGAO appears prohibitive. However, another AO technology option would be to use MEMs mirrors. The use of these mirrors in AO systems is taking place at UC Santa Cruz. It appears that a MEMs based replacement for the current AO systems could be very small and have low cost resulting from the inexpensive deformable mirror and smaller optical relay.

The following locations were considered for the location of these AO systems: interferometer basement and under the current AO Nasymth deck. The interferometer basement appears less viable because of the need to get an off axis natural tip tilt star (for interferometery with the LGS) to the basement through the existing coude optical train. In addition, the windows that thermally seal the interferometer may not pass enough visible light for wavefront sensing. It appears the fused silica windows would be suitable but that the zinc selenide windows may not be.

Junichi Meguro believes that the area under the Nasymth deck appears feasible based on a preliminary survey of the area. He noted the following points:

- Create space by adding structural members and sub-floor under Left Nasmyth Platform (LNP) to meet interferometery AO requirements.
- Addition of safety provisions around the interferometer AO area for installation and service of AO.
- Modifications to existing AO floor to bring beam to interferometer AO under LNP.
- Rearrange existing cables and lines under LNP.
- Install new cables and lines to interferometer AO system.
- Both NGAO and the interferometer AO systems are "fixed" in position, which minimizes chance of problems caused by vibration, shock, or damage due to movement

2.3. Swapping Current Keck AO and NGAO

When the current Keck Interferometer was being planned, the current Keck II AO system was already under construction. The adaptive optics system being built for Keck I would only be used for interferometery. A lengthy discussion was undertaken in the Keck community to determine if the Keck I AO system should be fixed in place on a Nasmyth deck or be removable from the deck like other instruments (DEMIOS, NIRSPEC, OSIRIS, IF Dual Star Modules). The result of this discussion was documented in KAON 165 [3]. It was ultimately decided that the Keck I system would be built as a fixed location instrument.

The following issues for movement of NGAO and a legacy AO system (either Keck I or II) on and off a Nasmyth platform are noted:

1. Legacy AO systems not designed for removal
    - Bench of legacy AO system not intended for relocation
    - Optics mounts not designed for relocation (shocks from movement of bench)
    - Legs supporting bench not kinematic
    - No lifting fixture on current bench
    - Use crane (lift) or cart (roll) to move AO on and off the Nasmyth deck
    - Redesign of WFS, DM, ACAM LBWFS, STRAP, cabling for removal
    - Redesign of cooling lines and air ducts for removal
    - Need to seal AO bench to maintain cleanliness when not in use
    - Alignment and calibration checks after reinstallation on Nasmyth deck
    - Performance of AO bench must be stable after each move

2. NGAO AO system would need to be designed for removal
    - Moving the June 2006 NGAO "point design" would be comparable to DEMIOS spectrograph
    - Reinforcement of Nasmyth Deck to support weight
    - If NGAO is cooled, need method to maintain temperature seal when off Nasmyth deck
    - Additional requirements/constraints on NGAO design, resulting in a higher cost system
    - Reevaluate after NGAO optical relay trade study is complete

3. Moving AO bench assembly may
    - Increase troubleshooting and testing of components and assembly
    - Increase time and manpower for reconfiguration
    - Require time and manpower for testing before science

    Increase chance of minor incidents due to movements and some major damage if lifted by crane
    - Increase chance of malfunction in general due to movement

Although this list may appear overwhelming, experience with DEIMOS indicates that a large instrument can be designed to be moved on and off the Nasmyth deck regularly.

3. Cost of Construction

One criterion that can be used to evaluate the proceeding options is cost of construction. Below we develop cost for construction of 2 identical AO systems (one for each telescope); based on using an adaptive secondary, a convention AO mirror (Xinetics), and MEMs mirror (Boston Micromachines). These are very rough order of magnitude estimates for the cost of these systems. As such, they are useful for comparison between various options but should not be taken as a final cost contract. The labor costs are estimated using $200,000 as the cost of 1 man years worth of labor, 1 full time equivalent (FTE) = $200K. This is just a round number and doesn't reflect the labor rate at any collaborating institution.

Hardware costs for an adaptive secondary are taken from conversations with Microgate and the Gemini ground layer AO feasibility study. Deformable mirror costs were taken from Xinetics and Boston Micro Machines, while costs for WFS optics and CCD are based on the Keck NGWFC project. The lasers for these systems are assumed to already exist at Keck or be purchased as part of the NGAO project. Each system is assumed to go through the standard development process at Keck observatory. This includes three design phases (system, preliminary, and detailed), fabrication phase, integration and test (I and T), acceptance test after I and T, I and T at telescope, and final acceptance testing. It was assumed that task 6, test jigs and fixtures, and task 10, telescope modifications, happen in parallel with other tasks. Therefore these tasks do not add to the overall duration of the project. The cost breakdown for an adaptive M2 option is shown in Table 1. The cost estimate for a conventional system with a Xinetics DM is shown in Table 2. The cost estimate for a MEMs based system is shown in Table 3. The far right columns of each table include a hardware cost breakdown for building one AO system; this is used at the fixed cost in calculating the fabrication costs (task 5).

Table 1: Costs of adaptive secondary AO system

ASM									
#	Task	Total cost	Cost 2nd System	Fixed Cost	Labor	Duration (Year)	FTE	Fabrication Fixed Costs	
1	Management & Support (all phases)	$440,000	$0	$0	$440,000	4.4	0.5	ASM + RTR	$2,300,000
2	System Design	$475,000	$0	$75,000	$400,000	0.5	4	Software	$70,000
3	Preliminary Design	$875,000	$0	$75,000	$800,000	0.5	8	WFS	$400,000
4	Detailed Design	$475,000	$0	$75,000	$400,000	0.5	4		
5	Fabrication	$8,740,000	$4,370,000	$2,770,000	$1,600,000	1	8		
6	Test Jigs and Fixtures	$250,000	$0	$50,000	$200,000	0.5	2	Total	$2,770,000
7	Integration and Test	$800,000	$400,000	$0	$400,000	0.5	4		
8	Acceptance Test	$80,000	$40,000	$0	$40,000	0.1	2		
9	Pack and Ship	$280,000	$140,000	$100,000	$40,000	0.1	2		
10	Telescope Modification	$120,000	$60,000	$0	$60,000	1	0.3		
11	System Integration and Test (Tel.)	$600,000	$300,000	$0	$300,000	0.5	3		
12	Final Acceptance Test	$80,000	$40,000	$0	$40,000	0.1	2		
13	System Documentation	$80,000	$40,000	$0	$40,000	0.1	2		
	Total	$13,295,000	$5,390,000	$3,145,000	$4,760,000	4.4			

Table 2: Hardware costs of conventional DM AO system

Standard DM									
#	Task	Total cost	Cost 2nd System	Fixed Cost	Labor	Duration (year)	FTE	Fabrication Fixed Costs	
1	Management & Support (all phases)	$340,000	$0	$0	$340,000	3.4	0.5	DM+HV	$700,000
2	System Design	$175,000	$0	$75,000	$100,000	0.25	2	Software	$70,000
3	Preliminary Design	$275,000	$0	$75,000	$200,000	0.25	4	RTR	$70,000
4	Detailed Design	$275,000	$0	$75,000	$200,000	0.5	2	WFS	$100,000
5	Fabrication	$3,480,000	$1,740,000	$940,000	$800,000	0.5	8		
6	Test Jigs and Fixtures	$110,000	$0	$10,000	$100,000	0.25	2	Total	$940,000
7	Integration and Test	$400,000	$200,000	$0	$200,000	0.5	2		
8	Acceptance Test	$80,000	$40,000	$0	$40,000	0.1	2		
9	Pack and Ship	$280,000	$140,000	$100,000	$40,000	0.1	2		
10	Telescope Modification	$40,000	$20,000	$0	$20,000	1	0.1		
11	System Integration and Test (Tel.)	$600,000	$300,000	$0	$300,000	0.5	3		
12	Final Acceptance Test	$80,000	$40,000	$0	$40,000	0.1	2		
13	System Documentation	$80,000	$40,000	$0	$40,000	0.1	2		
	Total	$6,215,000	$2,520,000	$1,275,000	$2,420,000	3.4			

Table 3: Hardware costs of MEMs DM AO system

MEMs DM									
#	Task	Total cost	Cost 2nd System	Fixed Cost	Labor	Duration (year)	FTE	Fabrication Fixed Costs	
1	Management & Support (all phases)	$340,000	$0	$0	$340,000	3.4	0.5	MEMs+HV	$200,000
2	System Design	$175,000	$0	$75,000	$100,000	0.25	2	Software	$70,000
3	Preliminary Design	$275,000	$0	$75,000	$200,000	0.25	4	RTR	$70,000
4	Detailed Design	$275,000	$0	$75,000	$200,000	0.5	2	WFS	$70,000
5	Fabrication	$2,420,000	$1,210,000	$410,000	$800,000	0.5	8		
6	Test Jigs and Fixtures	$110,000	$0	$10,000	$100,000	0.25	2	Total	$410,000
7	Integration and Test	$400,000	$200,000	$0	$200,000	0.5	2		
8	Acceptance Test	$80,000	$40,000	$0	$40,000	0.1	2		
9	Pack and Ship	$280,000	$140,000	$100,000	$40,000	0.1	2		
10	Telescope Modification	$40,000	$20,000	$0	$20,000	1	0.1		
11	System Integration and Test (Tel.)	$600,000	$300,000	$0	$300,000	0.5	3		
12	Final Acceptance test	$80,000	$40,000	$0	$40,000	0.1	2		
13	System Documentation	$80,000	$40,000	$0	$40,000	0.1	2		
	Total	$5,155,000	$1,990,000	$745,000	$2,420,000	3.4			

Any of these options require significant resources and time if selected. The cost of moving NGAO on and off the Nasmyth deck has not been estimated at this time pending completion of the AO optical relay trade study. A rough estimate at modify one legacy AO system to make it moveable is about $500,000 when costs of materials and labor are included. Using some means of matching polarization, as discussed in section 2.1, looks like the least costly option, if a suitable device can be found.

4. Recommendations and Future Work

At present, no ideal solution has been found for supporting the interferometer with NGAO. The following points are noted about each option:

Swapping Keck I/II with NGAO
- Hardware costs relatively low, compared to building new AO systems
- Cost of moving NGAO is higher than fixed NGAO

Matching NGAO to Keck
- Challenging to match polarization states
- Likely requires NGAO relay with K-mirror and in plane optics.
- No broad wavelength solution found
- Lower cost compared to other options, approximately 100K compared to millions

Two AO systems
- AO secondary on each telescope
  Elegant solution, but costly
  Utility of a shared capability could offset higher costs
- MEMs AO for each IF arm
  Relatively inexpensive
  Small footprint allows more mounting/packaging options

The lowest cost option will be matching NGAO to a legacy AO system. A more formal consultation with the Keck Interferometer team is recommended as a next step. Possible members of such a team could be Mark Colavita, Gene Serabyn, and Kent Wallace.

References

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