



Implication and Requirements for Interferometry with the Next Generation Adaptive Optics System

KECK ADAPTIVE OPTICS NOTE 428

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ABSTRACT

The Next Generation Adaptive Optics (NGAO) system must be compatible with interferometry using the two Keck telescopes. The implications of this observing capability are outlined in this note. Additional background information is provided about how requirements were derived. This note is not a complete requirements document but focuses on technical areas and constraints that will impact the NGAO design. Requirements related to safety, standard practices, and other generic requirements are generally not mentioned unless the interferometer imposes special constraints beyond those for other new instruments at the observatory.

1. Introduction

The requirements in this document are at a draft level appropriate for the system design phase of the Next Generation Adaptive Optics (NGAO) system. Further development of the requirements will take place in the next phase of the project (preliminary design). In particular, parametric performance requirements given at this stage are intended to indicate the scope and format of the requirements, but do not in all cases establish final values for the specified parameters. In some cases values for these parameters have yet to be established and are given as TBD.

It is important to understand that at this stage of development the requirements provide a basis for identifying the parameters that will be part of the instrument's specifications, but the values given are subject to change as the development of the instrument continues. During the next phase of the project, work will be done to refine the instrument's specifications into final specifications that will be reviewed at the detailed design review. The final specifications will also form the basis for the acceptance test criteria for the instrument.

2. Interferometry at Keck Observatory

The first interferometer project for the Keck Observatory was the interferometer funded through the NASA Origins project. This interferometer is generically referred to as the Keck Interferometer in this requirements document. This interferometer is the main interferometry instrument at Keck at the present time (Fall 2006). Keck also participates in interferometric combination of all telescopes on Mauna Kea with fiber optics, known as the Optical Hawaiian Array for Nanaoradian Astronomy ('OHANA). In 2006, the W. M. Keck Observatory was funded by NSF's Major Research Instrumentation (MRI) program to develop the capability to make phase referencing and astrometric measurements with the Keck Interferometer. The MRI will push the limiting magnitude of the current interferometer by use of dual star phase referencing in combination with LGS AO on each telescope; this project is referred to as the Keck MRI project.

The Keck Interferometer (KI) and participation in the 'OHANA Interferometer require AO systems on both Keck telescopes. At present, the KI and 'OHANA work only with the natural guide star mode of the AO systems. Currently, only the Keck II telescope is equipped with laser guide star capability. In 2008, a laser guide star will be commissioned on Keck I. The Keck MRI project plans to use LGS AO on both Keck I and Keck II, coupled with a phase referenced fringe tracker located in the Keck basement to perform astrometric observations with micro arc second precision.

The Keck Interferometer was designed to support five types of interferometry. These are visibility squared, nulling, differential phase, astrometry, and imaging. After the cancellation of the Keck outrigger telescopes in 2006, the imaging and astrometry modes of observation with the JPL/NASA interferometer were discontinued. All JPL/KI modes will have been handed over to the Keck Observatory on timescales relevant to NGAO. At that time JPL will have a limited role in



the interferometer at the Observatory. The possible modes of interferometry that NGAO may need to support are given in Table 1. How and if the NGAO system can be made compatible with these various observing modes will be evaluated during the system design phase. Ideally, no modifications to the interferometer itself would be required. However, expedient modifications to the interferometer beam train would also be acceptable. The trade offs between various concepts for supporting interferometry will be evaluated considering performance, cost, and schedule for both NGAO and the interferometry projects at Keck.

Instrument	Observing mode	Science wavelength	Current AO modes	Optical interface with AO		
KI	V-squared	J,H,K band	NGS	Coude	Single star	Collimated
KI	Nulling	N band	NGS	Coude	Dual Pupil	Collimated
KI	Differential phase	L,M band	NGS	Coude	Single Star	Collimated
'OHANA	V-squared	J,H,K band	NGS	Fiber Optics	Single Star	Focus
Keck/MRI	Astrometry	J,H,K band	LGS/NGS	Coude	Dual Star	Focus

Table 1. A list of future and current interferometer modes used at Keck Observatory. Science wavelengths are given by the approximate Johnson filter that they most closely overlap; see optical requirements section for detailed operating wavelength requirements. Optical interfaces are explained in more detail in section 4.

3. Overall System Requirements

3.1. Performance Requirements

TBD

3.2. Implementation Requirements

3.2.1. AO Corrected Beam

NGAO is required to provide an AO corrected beam to the interferometer.

3.2.2. Natural Guide Star AO Correction

The AO correction should be possible with a visual magnitude guide star as the only reference source for the AO system. AO correction must be comparable to or better than the Keck I/II systems after the NGWFC upgrades. The required brightness for the natural guide star is V magnitude of approximately 12 or brighter.

3.2.3. AO Image Sharpening

The NGAO system should be capable of correcting for TBD level of non common path aberration in the interferometer (i.e. image sharpening). It is not clear at this time what level of non common path aberration compensation NGAO will be required to provide with its correction elements. The current plans call for the instruments to have small optical aberrations. Legacy instruments such as NIRC2 and OSIRIS and the interferometer may be allowed large aberration budgets. In the case of focus aberrations, this requirement may also imply a range of motion along the optical axis for the wavefront sensor system.



3.2.4. Nuller Chopping

NGAO must be able to support a chopping mode for the interferometer Nuller. This requires small amplitude chopping (few arc seconds) with the AO loop remaining closed during all cycles of the chop. Ideally, AO correction should not be compromised when chopping is on.

3.2.5. DSM Opto-mechanical Interface to the Keck Interferometer

Currently, the Keck interferometer is optically interfaced to the Keck AO systems through an opto-mechanical system known as the Dual Star Module (DSM). The current interface is mounted on an optical table that can be removed from the AO enclosure in the same way as the AO instruments OSIRIS and NIRSPEC. If it is determined that NGAO should feed the interferometer, then it must be compatible with the current DSM interface or replicate its functionality.

3.3. Design Requirements

TBD

4. Optical Requirements

4.1. Performance Requirements

The fundamental observable in interferometry is the complex visibility because it can be related to the image brightness distribution through the van Cittert-Zernike theorem. In general, the visibility is a complex quantity, $\Gamma = Ve^{-i\phi}$, where V is the visibility amplitude and ϕ is the fringe phase. The visibility is normalized such that $0 < V < 1$. Keck is a two element non co-phased interferometer; as such the fringe phase is corrupted by atmosphere turbulence. As a result, only the visibility is a useful quantity. For technical reasons, the interferometer directly estimates the visibility amplitude squared, V^2 , and for this reason, many of the requirements for the interferometer are stated in terms of this quantity.

4.1.1. Polarization Matching

In order to achieve interference between two telescopes, the electromagnetic field from each telescope must be in the same polarization state. In the limiting case of orthogonal polarization states between the telescopes, no interference would result. The current KI achieves polarization matching by keeping the number and angle of all the reflections the same in both beam trains from each telescope. This design methodology suggested by Traub¹ is standard practice in the stellar interferometry field. However, other options may be implemented for interferometry with NGAO. The loss of visibility, V^2 , with differential s-p phase shift, ϕ , between telescopes is given by

$$\Delta V^2 = \sin^2(\phi/2) \tag{1}$$

For further details on polarization effects in interferometry, see references by Traub¹ and Ridgeway². The differential s-p phase shift in the current Keck Interferometer is measured at 6 degrees resulting in a loss in V^2 of 0.003. This needs to be maintained for all science wavelengths that the interferometer uses for fringe tracking and nulling. This requirement is driven by the nulling mode of the interferometer. For V^2 observations, 0.003 would be a negligible and trivially calibrated effect.



4.1.2. Image and Pupil Rotation Symmetry

The image rotation between the two telescopes is also required to be the same for interference between beams. This constraint is met in the current KI by matching the number and angle of reflections between the two beam trains, resulting in images at the end of the beam train with the same rotation. The constraint is closely coupled to the polarization requirement. The loss in visibility, V^2 , with differential image rotation, θ , between telescopes is given by

$$\Delta V^2 = \sin^2(\theta) \quad (2)$$

The differential rotation between beams in the Keck Interferometer is estimated to be 2 degrees resulting in a V^2 loss of 0.001. This requirement is driven by the nulling mode of the interferometer, which also requires 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.

4.1.3. AO Strehl Mismatch (Intensity Mismatches)

The performance of the Keck Adaptive Optics systems affects the wavefronts entering each side of the KI. The quality of AO correction is given by the Strehl ratio, S . This quantity is directly proportional to the visibility, V , assuming identical effects on both telescopes, when good AO correction is achieved, see ref. 3. In this case, the visibility would be reduced by a factor proportional to the Strehl ratio in each arm of the interferometer. For interferometers that only operate on a single spatial mode such as the Keck Interferometer, the loss of visibility from wavefront phase errors can be partially mitigated by the use of a single mode fiber to spatial filter the wavefront after combination. In this case the visibility is reduced due to mismatches in the intensities, I_1 and I_2 , coupled into the fiber in the beam combiner. The reduction in V^2 , is given by

$$\Delta V^2 = 1 - \frac{4I_1I_2}{(I_1 + I_2)^2} \quad (3)$$

Further details about the use of single mode fibers in interferometry are given in reference 4 by Shaklan. Mismatches in the coupled intensities are directly related to the Strehl ratio provided by each telescope's AO system. The current intensity mismatch between the K1 and K2 AO systems from Strehl is 22% or a ratio of I_2/I_1 of 1.22. The resulting loss in V^2 is 0.010. If NGAO achieves a K band Strehl as high as 0.9, then the Strehl mismatch could be as high as 66% or an intensity ratio of 1.5. The resulting loss of V^2 would be 0.04.

4.1.4. Wavelength Coverage

As noted in Table 1, the current and future modes of the interferometer will cover the wavelength range from 1.0-14.0 microns. (This approximates the transmission of the astronomical bands J through N).

4.1.5. Transmission

Transmission of star light in the range 1.0-14 microns should be the same as current Keck II and Keck I interferometers after upgrades for the MRI project. The MRI project has specified several new Dichroics for the Keck I and Keck II AO benches that provide a higher throughput. Exact transmission specification is TBD. Although a transmission mismatch between the telescopes reduces the visibility, the effect is typically small. The resulting loss is given by equation 3 above.



If the transmission loss in the two arms of the interferometer were 0.4 and 0.45, the loss in V2 would be 0.0035.

4.1.6. Residual Tilt

The beam from each telescope in the KI system must maintain pointing to a fraction of the diffraction limit at the interferometer science wavelength. In the current KI, this is accomplished by fast tracking mirrors in the AO system and in the interferometer basement. Currently, the rms tilt error between K1 and K2 is 0.007 arc seconds.

4.1.7. Optical Quality

The current optical quality of the KI beam train has been measured to about 100 nm rms. The number represents the total for all optics in the interferometer beam train. These aberrations are not corrected by the AO system. Any non common path aberrations added inside NGAO or on the replacement for the DSM must not increase these aberrations. The interferometer beam train has about 20 surfaces. This implies that each surface is accurate to about 20 nm rms or better.

4.1.8. Nuller Specific Optical Requirements

The polarization, image rotation, residual tilt, optical quality, and Strehl mismatch requirements also apply to the nulling mode of the interferometer. A Nuller leakage budget from Mark Colavita of JPL is reproduced in the Appendix of this note.

4.1.9. Field of View

The current Keck I and Keck II AO system provide for using a natural star as much as 30 arc seconds away from the science object. NGAO must be able to retain this capability to support IF natural guide star observations. For future interferometric observations that will use laser guider stars, the ability to select a natural tip tilt star as much as 30 arc seconds away would be required. Additionally, the MRI project will require the capability to send light from two stars located up to 30 arc seconds apart into the primary (on axis star) and secondary (off axis star) coude trains, see section 4.2.1.

4.1.10. Summary Optical Parameters

<i>Parameter</i>	<i>Min.</i>	<i>Typ.</i>	<i>Max.</i>	<i>Units</i>	<i>Notes</i>
Polarization matching					
Differential s-p phase shift		-	6	Degrees	
Image rotation symmetry					
Differential image rotation			2	Degrees	
Strehl mismatch					
Intensity ratio		-	22	Percent	
Wavelength coverage					
Inclusive	1.0	-	14.0	μm	
Transmission					
	TBD			Percent	
Residual Tilt					
	0.007			Arc seconds rms	
Optical quality					
	100			Total nm rms	
Field of view					
	30			Arc seconds	



4.2. Implementation Requirements

4.2.1. Optical Beam Modes

NGAO or NGAO in combination with a modified DSM must be able to provide the following optical interfaces to the interferometer. Note that dimensions given below are for the on axis beam only, actual optical surface diameters must be larger to minimize diffraction and vignetting.

1. AO corrected collimated beam for V^2 to the KI coude train primary beam.
2. AO corrected collimated beam with pupil split for Nulling to the coude train primary and secondary beams.
3. AO corrected $f/15$ beam focused at the 'OHANA injection fiber.
4. AO corrected beam and the ability to select light from two stars separated by 30 arc seconds for the MRI interferometry project. The beams are delivered to the Keck Interferometer coude train primary and secondary beams with one star in each coude train.

On the current Keck DSM the telescope pupil inscribed diameter of 9m maps to 112 mm diameter circle for collimated beam in V^2 operation. Drawing of the current KI DSM interface is shown in Figure 1 and Figure 2

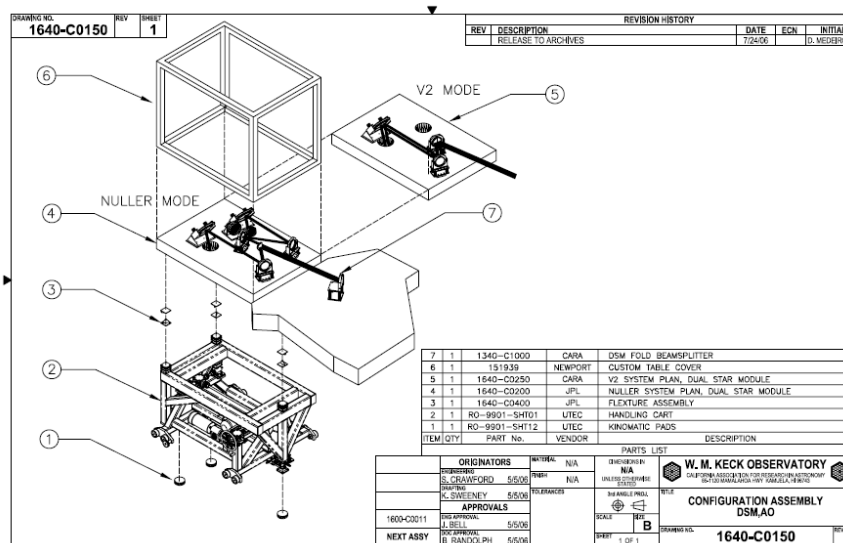


Figure 1. Overview of AO Bench, and current KI Dual Star Module (DSM). Optical layout for both V^2 and nulling are shown. The switch between V^2 and nulling is achieved by moving optics on the DSM bench, not by a substitution of one bench for the other. Original drawing number 1640-c0150.

4.2.2. Meteorology Beam Suppression

NGAO or NGAO in combination with a modified DSM must be capable of supporting the metrology beams from the KI and MRI interferometers.

4.3. Design Requirements

TBD



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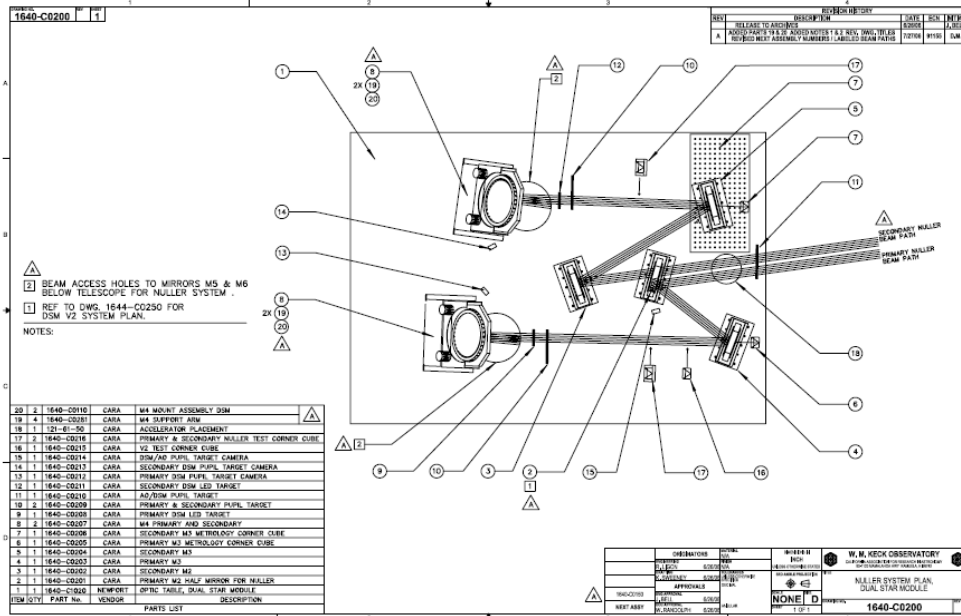


Figure 2 Overview of optics on the DSM bench for nulling. Original drawing number is 1640-C0200.

5. Mechanical Requirements

5.1. Performance Requirements

5.1.1. Vibrations

This section is taken directly from the MOSFIRE requirements which should be consistent with the new vibrations standards at the observatory.

Vibration isolation should be employed as required to isolate sources of vibration within the NGAO instrument due to moving components such as fans, pumps, and motors. NGAO should meet all performance and operating requirements when installed in a vibration environment that conforms to the Generic Vibration Criteria⁵ Curve “C” as shown in Figure 3. NGAO should not produce vibrations that result in rms velocities in excess of those given in curve “C” of Figure 3.

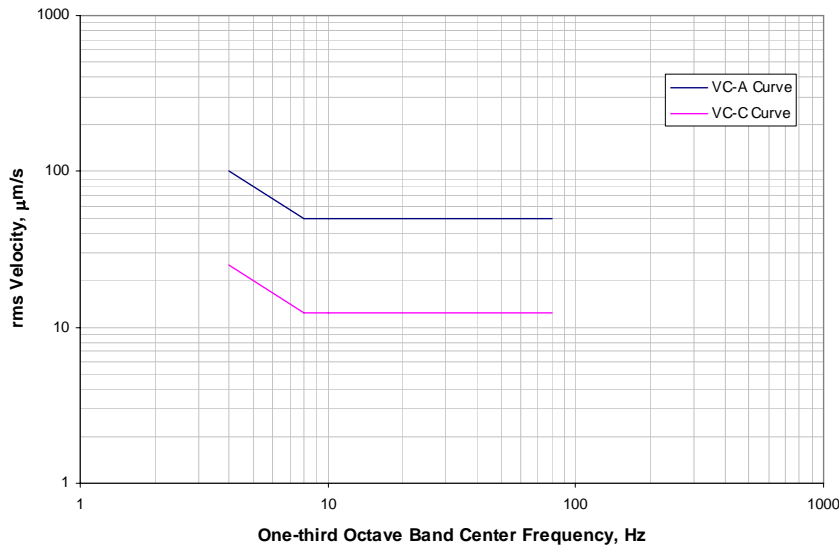


Figure 3: Keck I telescope equipment vibration limits

5.2. Implementation Requirements

5.2.1. Alignment

The NGAO optical mechanical interface must be capable of supporting alignment tolerances and tools consistent or better than the current KI beam train. For example, the current AO bench hosts a corner cube to aid in aligning the interferometer to the mechanical boresight of the AO system and telescope. With this cubed unblocked we are able to generate a reference spot on the AO acquisition camera. Need ability to send a white-light AO stimulus down the beamtrain for testing; with flux out to K band, exact intensity level is TBD.

5.2.2. Mechanism for Optical Interfaces

NGAO or NGAO in combination with a modified DSM must be able to provide automated mechanisms for control and positioning of optics for the following optical interfaces to the interferometer:

1. AO corrected 4" collimated beam for V^2 to the KI coude train primary beam.
2. AO corrected 4" collimated beam with pupil split for Nulling to the coude train primary and secondary beams.
3. AO corrected f/15 beam focused at the 'OHANA injection fiber.
4. AO corrected f/15 beam and the ability to select light from two stars separated by 30 arc seconds for the MRI interferometry project. The beams are delivered to the Keck Interferometer coude train primary and secondary beams with one star in each.

In the current AO system the beam is fed to the KI from a moving dichroic. The OHANA and possibly MRI systems are fed from an optical interface plate that is mounted on the AO bench itself. The current DSM can be removed and replaced with another AO capable instrument (NIRSPEC and OSIRIS). If NGAO will have a removable DSM, some mechanism must be available for its removal (motorized cart, crane, etc.)

5.3. Design Requirements

TBD

6. Electronic Requirements



6.1. Performance Requirements

6.1.1. Power Dissipation

Power dissipation requirement for IF is consistent with general NGAO requirements to suppress non common path turbulence.

6.1.2. Electrical Noise Suppression

Electrical noise suppression requirements for IF are consistent with NGAO general requirements.

6.2. Implementation Requirements

NGAO must provide accelerometers on the AO bench and on the DSM or its replacement. These accelerometers measure vibration along the optical path and are used in the KI fringe tracker control system. The interface for accelerometer data acquisition electronics and mechanism control are hosted in an electronics rack located inside the current AO system enclosure. NGAO must replicate the functionality currently located in this rack.

6.3. Design Requirements

TBD

7. Safety Requirements

Interfacing of NGAO to the interferometer at Keck Observatory imposes no extra safety standards on NGAO.

8. Software Requirements

8.1. Performance Requirements

TBD

8.2. Implementation Requirements

Further details on the exact keywords and EPICS channels used in the interface between the KI and the AO system can be found in “Summary of External Interfaces in the Current WFC and Implications for the NGWFC Design”, KAON 315 Erik Johansson.

8.2.1. Interferometer Tracking Offload

The NGAO system must have the ability to re-point (offload) the beam leaving NGAO such that the interferometer tip tilt tracking system does not exceed the angular range of its fast tracking mirror.

8.2.2. Interferometer, Telescope, and NGAO Coordination

The NGAO plus Keck Telescope system must be able to acquire a target and lock the AO loop when commanded by the IF sequencer software. The NGAO system should be able to set the AO system frame rate, loop gain, wfs background levels, etc. to the correct values when given information about the star magnitude and spectral type from the IF sequencer software.

8.2.3. Nuller Chopping



NGAO must be able to support a chopping mode for the interferometer Nuller. This requires small amplitude chopping (few arc seconds) with the AO loop remaining closed during all cycles of the chop. Ideally, AO correction should not be compromised when chopping is on, except during the chop transitions.

8.3. Design Requirements

TBD

9. Interface Requirements

9.1. Performance Requirements

9.2. Implementation Requirements

The NGAO system must have the ability to re-point (offload) the beam leaving NGAO such that the interferometer tip tilt tracking system does not exceed the angular range of its fast tracking mirror.

The NGAO plus Keck Telescope system must be able to acquire a target and lock the AO loop when commanded by the IF sequencer software. The NGAO system should be able to set the AO system frame rate, loop gain, wfs background levels, etc. to the correct values when given information about the star magnitude and spectral type from the IF sequencer software. The AO acquisition time must be less than 2 minutes.

Further details on the exact keywords and EPICS channels used in the interface between the Keck interferometer and the AO system can be found in Johansson⁶ KAON 315.

9.3. Design Requirements

10. Reliability Requirements

The KI has many subsystems and must have a stringent requirement on the reliability and efficiency of each subsystem including AO. AO uptime for the interferometer must be greater than 95%.

10.1. Performance Requirements

TBD

10.2. Implementation Requirements

TBD

10.3. Design Requirements

TBD

11. Spares Requirements

TBD

12. Service and Maintenance Requirements

TBD



13. Documentation Requirements

TBD

14. Glossary

15. References

1. W. A. Traub, "Polarization effects in Stellar Interferometers", in *High Resolution Imaging by Interferometry*, F. Merkle ed, Proc. ESO Conf. 29, 1029-1038 (European Southern Observatory: Garching Germany, 1988).
2. S.T. Ridgway and W. G. Bagnuolo, "Polarization Revisited" CHARA Technical Report, TR-28, 1996.
3. T. A. ten Brummelaar, W. G. Bagnuolo, and S. T. Ridgway, "Strehl ratio and visibility in long-baseline stellar interferometry", *Optics Letters*, vol. 20, num. 6, 1995.
4. S.B. Shaklan, M.M. Colavita, and M. Shao, "Visibility calibration using single-mode fibers in a long baseline interferometer", in *High Resolution Imaging by InterferometryII*, J. M. Beckers and F. Merkle ed, Proc. ESO Conf. 39, 1271-1283 (European Southern Observatory: Garching Germany, 1992).
5. Gordon, Colin G. "Generic Criteria for Vibration-Sensitive Equipment", in *Vibration Control in Microelectronics, Optics, and Metrology*, Proceedings of the SPIE Vol. 1619, pp. 71-85., Gordon, Colin G. ed. SPIE 1992
6. E. Johansson, "Summary of External Interfaces in the Current WFC and Implications for the NGWFC Design", Keck Adaptive Optics Note 315 (KAON 315).



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16. APPENDIX

The following error budgets were prepared by Mark Colavita of JPL.

Nuller leakage terms, included both NGAO related terms and terms unique to Nuller instrument.

Systematic Leakage Error Budget			wavelength	9.5	um	sub-ap diameter	5.6	m	DSM diam	70	mm	pinhole size p'	1.63	diff limit	0.35	arcsec	shear scale factor	0.4	shear scale	78	mm	Lyot factor	0.75
Term	Expression	Input	Value	Bracewell Leakage	Null	Correlation	Correlated Leakage	Null	Calibration	Leakage Uncertainty (both stars)	Null												
single-mode terms																							
1	OPD fluctuations	$L = \frac{1}{4} \sigma_{\text{OPD}}^2$	$\sigma_{x_1-x_2}$, rms OPD difference (nm)	225	0.0055	180	0.5	0.0028	361	0.5	0.0014	722											
2	OPD offset	$L = \frac{1}{4} (\sigma_{\text{OPD}})^2$	x_1-x_2 , OPD difference (nm)	50	0.0003	3650	0.5	0.0001	7310	0.75	0.0000	29200											
3	Intensity balance	$L = \frac{1}{4} [1-4I_1I_2/(I_1+I_2)^2]$	I_1/I_2-1 , intensity balance	25%	0.0031	323	0.5	0.0015	647	0.75	0.0004	2590											
4	Intensity fluctuations	$L = 1/8 \sigma_{I_i}^2$	σ_{I_i} , intensity rms per arm	1.3%	0.0000	47300	0.5	0.0000	94600	0.5	0.0000	2E+05											
aberration terms																							
p' is pinhole size relative to σ/d																							
5	Tilt offset	$L \approx 0.1 (t'p')^2$	t' , total vector tilt (waves)	0.040	0.0004	2350	0.5	0.0002	4700	0.75	0.0001	18800											
arcsec/axis/beam, sky 0.007																							
6	Tilt fluctuations	$L \approx 0.1 (t'p')^2$	t' , total vector tilt (waves)	0.040	0.0004	2350	0.5	0.0002	4700	0.5	0.0001	9400											
arcsec/axis/beam, sky 0.007																							
7	Shear	$L \approx \sigma_{\text{shear}}^2 (s'p')^2$ $\sigma = \text{Lyot factor}$	s' , total shear (frac of beam diameter)	0.100	0.0080	125	0.5	0.0040	250	0.5	0.0020	501											
mm/axis/beam, DSM 3.5																							
8	Focus + astig	$L \approx 3 (w'p')^2$	w' , total rms phase difference in those modes (waves)	0.025	0.0050	200	0.5	0.0025	401	0.75	0.0006	1600											
P-V per beam, HeNe 0.9																							
9	Coma + trefoil	$L \approx 0.8 (w'p')^2$	w' , total rms phase difference in those modes (waves)	0.025	0.0013	752	0.5	0.0007	1500	0.75	0.0002	6010											
P-V per beam, HeNe 0.9																							
polarization terms																							
10	Image rotation	$L = \frac{1}{4} \sigma_{\text{rot}}^2$	σ_{rot} differential rotation (deg)	2	0.0003	3280	0.75	0.0001	13100	0.75	0.0000	52500											
11	Polarization phase shift	$L = 1/16 \sigma_{\text{ps}}^2$	σ_{ps} differential s-p phase shift (deg)	6	0.0007	1450	0.75	0.0002	5830	0.75	0.0000	23300											
Total Leakage:				0.025				0.012			0.0096												
Exclude SM terms:										0.0060													



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V^2 reduction, only terms effected by NGAO

V2 reduction terms							
							$SNR^2 \propto (I_1+I_2)^2 V^2 / (I_1+I_2+R)$
Term	Expression	Input	Input Value	V^2	ΔV^2	Sensitivity loss, RN-limit (mags)	$\partial V^2 / (\partial I)$
Intensity balance	$\Delta V^2 = 1 - 4I_1 I_2 / (I_1 + I_2)^2 \sim 1/4 \Delta^2$	I_2/I_1 , intensity ratio	1.50	0.960	0.0400	0.02	-0.19
Image rotation	$\Delta V^2 = \sin^2(\Delta \theta) \sim \Delta^2$	Δ differential rotation (deg)	2	0.999	0.0012	0.000662	
Polarization phase shift	$\Delta V^2 = \sin^2(\Delta \theta) \sim 1/4 \Delta^2$	Δ differential s-p phase shift (deg)	6	0.997	0.0027	0.001489	
				Totals	0.956	0.044	0.02