Invited Paper

KOLA: A Concept for an Optical Multi-Conjugate Adaptive Optics System for W.M. Keck Observatory

Jessica R. Lu[a,], Rich Dekany[b], Brianna Peck[a], Antonin Bouchez[c,], Max Millar-Blanchaer[d], Phil Hinz[e], Kodi Rider[g], Mark Chun[f,], Peter Wizinowich[c,], Lianqi Wang[h,], Steph Sallum[i,], Brooke DiGia[a], and Charles-Antoine Claveau[a]

[a]University of California, Berkeley, CA, USA
[b]Caltech Optical Observatory, Pasadena, CA, USA
[c]W. M. Keck Observatory, Waimea, HI, USA
[d]University of California, Santa Barbara, CA, USA
[e]University of California, Santa Cruz, CA, USA
[f]Institute for Astronomy, University of Hawaii, Manoa, HI, USA
[g]Space Sciences Laboratory, University of California Berkeley, Berkeley, CA, USA
[h]Thirty Meter Telescope International Observatory, Pasadena, CA, USA
[i]University of California, Irvine, CA, USA

ABSTRACT

We present progress on a conceptual design for a new Keck multi-conjugate adaptive optics system capable of visible light correction with a near-diffraction-limited spatial resolution. The KOLA (**K**eck **O**ptical **L**GS **A**O) system will utilize a planned adaptive secondary mirror (ASM), 2 additional high-altitude deformable mirrors (DMs), and $\gtrsim 8$ laser guide stars (LGS) to sense and correct atmospheric turbulence. The field of regard for selecting guide stars will be 2' and the corrected science field of view will be 60". We describe science cases, system requirements, and performance simulations for the system performed with error budget spreadsheet tools and MAOS physical optics simulations. We will also present results from trade studies for the actuator count on the ASM. KOLA will feed a new optical imager and IFU spectrograph in addition to the planned Liger optical + infrared ($\lambda > 850$ nm) imager and IFU spectrograph. Performance simulations show KOLA will deliver a Strehl of 12% at g', 21% at r', 53% at Y, and 87% at K bands on axis with nearly uniform image quality over a 40"×40" field of view in the optical and over 60"×60" beyond 1 μm. Ultimately, the system will deliver spatial resolutions superior to HST and JWST (∼17 mas at r'-band) and comparable to the planned first-generation infrared AO systems for the ELTs.

Keywords: adaptive optics

1. INTRODUCTION

Large optical and infrared (OIR) telescopes are prized both for their light-collecting power and their ability to resolve fine structures in the Universe. 8-10 m class ground-based telescopes achieve high spatial resolution with adaptive optics (AO) systems that measure and correct the blurring effects of the Earth's atmosphere. AO systems with high sky-coverage are essential for studying supermassive black holes and their environments, faint and distant galaxies evolving over cosmic time, transient exploding stars that produce black holes and neutron stars, binary and multiple star systems that host planets or compact objects, storms and volcanoes on Solar System planets and moons, and searching for free-floating black holes through gravitational lensing. High sky-coverage is achieved by using a bright laser guide star (LGS) when no natural guide star (NGS) is available near a faint science target.

Send correspondence to J.R. Lu:
E-mail: jlu.astro@berkeley.edu

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Historically, most LGS AO systems delivered moderate image quality (Strehl$\sim$0.4) and high spatial resolution ($\sim$50-70 mas) at *infrared* wavelengths (e.g. Keck 1&2 AO, VLT SINFONI, Gemini North AO). The new VLT MUSE Narrow-Field mode delivers AO correction (Strehl$\sim$ 0.05; FWHM$\sim$75 mas) at red-optical wavelengths and is in high demand.[1] The extremely large telescopes (ELTs) currently planned or under construction will deliver dramatically improved spatial resolution ($\sim$15 mas); but primarily at infrared wavelengths for first-generation LGS AO systems.[2,3] Both VLT and Keck have identified a strategic need for near-diffraction-limited, visible-light LGS AO systems to improve spatial resolution by $\sim 3\times$ to $\sim$15 mas over moderate (30"-60") fields and extend imaging and spectroscopic coverage[*].[4] The VLT MAVIS project seeks to address this strategic need.[5]

We present a feasible design for a near-diffraction-limited, visible-light LGS AO system for the W. M. Keck Observatory. The Keck Optical LGS AO (KOLA) system would deliver a spatial resolution of <20 mas at 500 nm over a >60" diameter field of view for targets over most of the sky. In this paper, we present KOLA science requirements, performance trade studies, and basic system parameters. KOLA would deliver complementary science capabilities to major forthcoming ground- and space-based facilities, including JWST, ALMA, Euclid, Roman, SPHEREx, Rubin, and ELT's achieving diffraction-limited near-infrared (NIR) image quality (Figure 1).

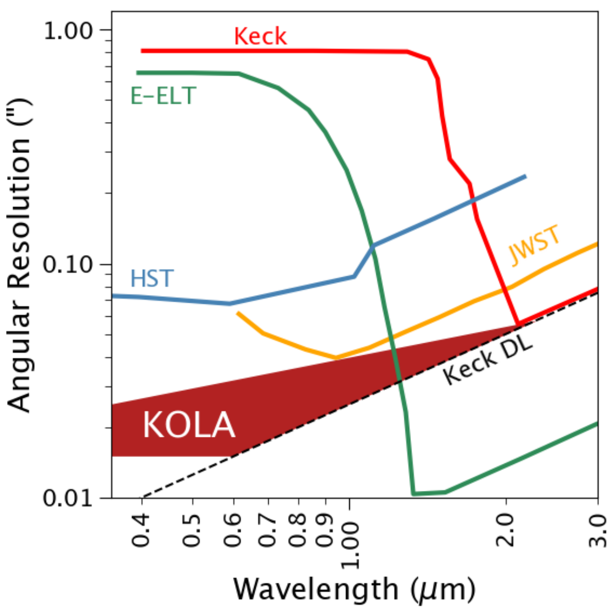

Figure 1 - Expected spatial resolution of KOLA, a visible and infrared light multi-conjugate AO system. KOLA will extend the wavelength range over which near-diffraction-limited performance can be obtained and expand the corrected field of view to $\sim$60".

2. KOLA SCIENCE CASE AND REQUIREMENTS

Increased spatial resolution and sensitivity at optical wavelengths is essential for advancing a range of science fields. A visible light AO workshop held in 2022 Apr attracted 76 participants and 15 major science cases were identified. These ranged from constructing a black hole and neutron star demographic census, characterizing exoplanet atmospheres, monitoring weather and volcanic activities on Solar System bodies, resolving the environments around supermassive black holes, probing stellar populations and binarity at different ages and metallicities, and understanding how stars and planets form. These science cases, listed in Table 1, require visible-light spatial resolutions higher than can be achieved with HST, JWST, or ground-based AO in the infrared. Broadly speaking, the KOLA system would be a work-horse AO system enabling advances across all astrophysics fields.

[*]Keck 2035 Strategic Plan

Table 1 - Example KOLA Science Cases

Number	Science Case	Measurement Requirements
SCI01	**BH and NS Demographics:** Find and weigh isolated black holes and neutron stars in the Milky Way Bulge via gravitational lensing.	Case A: $\sigma_{ast} < 60$ mas on R=22 stars in crowded fields out to 10 kpc, $FOV \gtrsim 30$" for sufficient number of astrometric reference stars. Case B: $\theta_{FWHM} \lesssim 18$ mas to detect lensed images separated by 9 mas for BHs out to 1 kpc.
SCI02	**BH and NS Binaries:** Find and weigh black holes and neutron stars in binary systems within 3 kpc.	$\sigma_{ast} < 100$ mas to detect astrometric wobble, $\sigma_{RV} < 5$ km/s at R=21 to confirm with RV wobble.
SCI03	**Solar System Activity:** Monitor and study transient storms and volcanic activity on inner and outer Solar System planets, moons, and small bodies.	$\theta_{FWHM} < 23$ mas to resolve 500 km/s features on Uranus and Neptune, 25 km features on Mars and Venus, FOV >50" to fully image Jupiter, Mars, Venus, and cometary tails, $\Delta\lambda = 380 - 900$ nm to cover CN on comets and numerous atmospheric features.
SCI04	**SMBH Environments:** Resolve SMBH environments, weigh the SMBH, characterize the surrounding stellar population.	Case M31 Individual Stars: $\theta_E \lesssim 15$ mas to resolve multiple stars and measure proper motions of > 1 mas/yr with $\sigma_{ast} < 100$ mas astrometric precision. Case B Resolve Sphere of Influence: $\theta_{FWHM} < 18$ mas to resolve sphere of influence around $\sim 10^6$ $M_\odot$ black holes at 10 Mpc and $\Delta\lambda$ = 400 - 800 nm to identify young nuclear clusters (Figure 2.
SCI05	**Dense Stellar Populations:** Probe stellar populations and binarity in dense environments at different ages and metallicities.	Case A: $\theta_{FWHM} < 18$ mas to resolve bulge and nuclear populations in galaxies out to Virgo, $\Delta\lambda$ = 350 - 2300 nm. Case B: $\theta_{FWHM} < 18$ mas to resolve 1AU binaries at 50 pc (e.g. Hyades cluster), 2.5 AU binaries at 150 pc (e.g. Pleiades, Taurus cluster), and 50 AU binaries at 2500 pc (nearest globular clusters). $\Delta\lambda$ = 350 - 2500 nm to spectral type stars, white dwarfs, and brown dwarfs.
SCI06	**Star and Planet Formation:** Chemically map inner and outer disks and accretion flows onto protoplanets or protostars in proto-stellar systems in a range of environments.	$\theta_{FWHM} = 15$ mas to resolve <7 AU features at 450 pc (e.g. Orion) and <2.5 AU at 150 pc (Taurus, Ophiuchus), $\Delta\lambda$ = 600 - 2300 nm to probe Hα, forbidden O, S, N lines, and a wide range of molecules.
SCI07	**Exoplanet atmospheres:** Monitor activity, accretion, weather, and habitability tracers including UV, Hα and numerous atomic and molecular species.	5-9 mag contrast at 656 nm, 10-14 mag contrast at 350 nm, $\Delta\lambda$ = 350 - 2300 nm.

The spatial resolution advances are essential in the case of resolving SMBH spheres of influence in other galaxies and studies of stellar populations. Figure 2 shows the projected radius of influence on the sky for SMBHs at different distances and masses. The spatial resolution of TMT IRIS at 2 μm and KOLA at 0.7 μm is comparable, offering the unique ability to probe both young (blue) and old (red) stellar populations surrounding SMBHs and understand the interplay between the evolution of the SMBH and its host galaxy. A particularly unique case is our nearest neighbor spiral galaxy, M31 (Andromeda), which harbors a 100x more massive SMBH than the Milky Way and an unusual nuclear star cluster, shown in Figure 3. Increased spatial resolution at blue-optical wavelengths will allow us to detect individual stars and measure their proper motions and perhaps accelerations. We can weigh the black hole and understand how the young nuclear cluster was formed in this largely gas-free region.

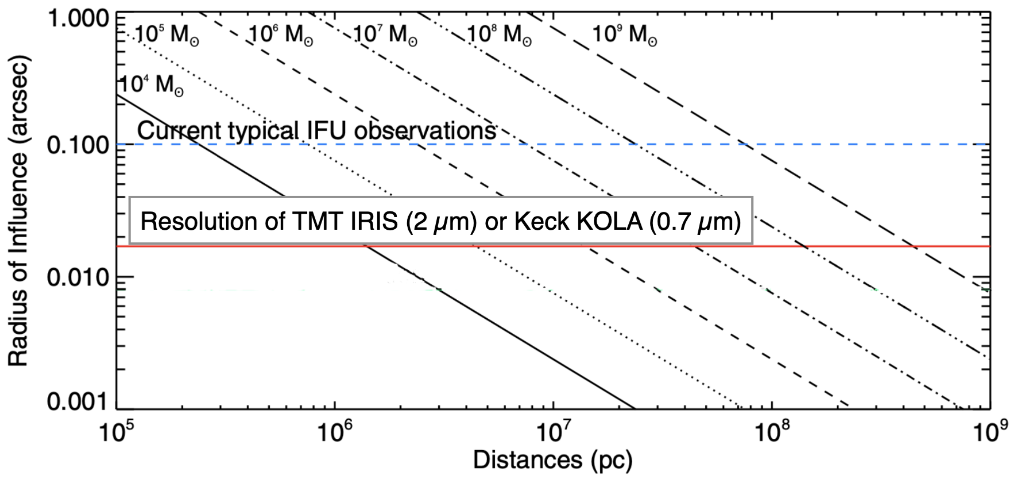

Figure 2 The projected radius of influence of a supermassive black hole (SMBH) at different distances. Current AO systems deliver resolutions sufficient to probe SMBH environments in only the closest galaxies (*dashed blue*). Both the ELTs and the KOLA system on Keck will probe more distance SMBHs or lower mass black holes (*red solid*). Figure modified from.[6]

Some of the cases, such as finding and weighing free-floating stellar-mass black holes, require high astrometric precision, regardless of wavelength. Others, such as exoplanet characterization and activity monitoring on Solar System planets and moons, require high spatial resolution over a broad spectral range to probe specific spectral features. Several cases require larger fields of view than typical single-conjugate AO systems deliver in order to cover extended targets (stellar populations, galactic centers, Solar System targets such as Venus and Jupiter) or to include reference stars for photometric or astrometric calibration (isolated black holes via astrometric microlensing or astrometric binary orbits, intermediate mass black holes in globular clusters via proper motions). The majority of these cases require high sky-coverage including coverage of the Galactic poles or deeply obscured regions towards the inner Galaxy.

We have identified the following system requirements for a new AO system to be deployed on the Keck telescope that can address the needs of the science cases listed above. To achieve high image quality, high sky coverage, and moderate fields of view (30-60") at visible and infrared wavelengths will require a laser-guided, multi-conjugate adaptive optics system. Such a system allows 8-10 m class telescopes to remain competitive and complimentary with the next-generation of 30 m class telescopes. The diffraction-limit ($\sim$13 mas at 500 nm) in the visible on a 10 m telescope such as Keck provides nearly identical spatial resolution to the infrared AO systems planned for the ELTs (Figure 1).

Table 2 - KOLA Science Requirements

Number	Requirement
1	The AO system will deliver AO-corrected light to science instruments from 350 - 2500 nm.
2	The AO system will deliver a spatial resolution that is within 25% of diffraction limited down to 18 milli-arcseconds.
3	The AO system will have a sky coverage >50% at the Galactic poles with a maximum 50% encircled energy radius of 50 mas.
4	The corrected field of view will equal or exceed 60" in diameter.
5	Images will have a strehl of 0.2 at 650 nm over a 60" diameter field of view for 3 TT stars H<12 mag within 60" radius.
6	AO correction will be tunable to deliver strehl=0.5 over 3" radius fields of view at 500 nm for on-axis objects with V<6 mag serving as natural guide stars or with faint objects with 3 TT stars of H<12 mag within 15" radius.

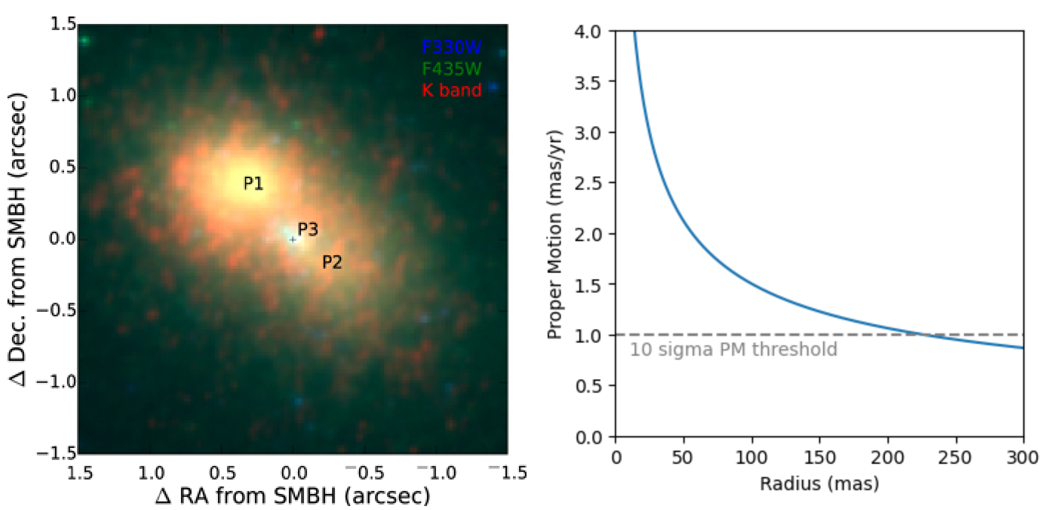

Figure 3 The nuclear of M31 (Andromeda) shows the critical need for optical and infrared coverage to characterize stellar populations (*left*). Individual stars orbiting the SMBH can be measured within ∼ 0.2" if they can be resolved at spatial resolutions of ∼20 mas (*right*). Confusion will be the limiting factor on the ability to detect accelerations and refine the black hole mass and the enclosed stellar and dark mass within the sphere of influence (∼1"). Left panel modified from.[7]

3. KOLA PERFORMANCE AND DESIGN TRADES

To achieve the science requirements listed above, KOLA will consist of a multi-conjugate adaptive optics system likely deployed on the Keck 1 telescope on the Nasmyth platform. As a baseline design, KOLA will include 3 deformable mirrors, including 1 adaptive secondary mirror (ASM), conjugate to -100 m, 6 km, and 10 km. Three tip-tilt-focus (TTF) natural guide star wavefront sensors can be deployed over a 120" diameter field. A LGS constellation will be launched from the telescope elevation ring and distributed on the sky in a circle of 60" in diameter; the corrected science field will thus be 60" across. Each LGS beacon will have its own high-order wavefront sensor with the number of sub-apertures matched to the number of ASM actuators. The number of actuators, number of LGS beacons, power per beacon, and loop rate are explored below.

To optimize the KOLA design, we first use the Keck Error Budget Spreadsheet v3.1.5,[8] which uses analytic descriptions to estimate wavefront errors (WFE), predicts Strehl and FWHM at a wide range of wavelengths, and is fast and easy to run for a large grid of different system parameters. KEBS has been validated against on-sky observations with the current Keck single-conjugate AO system. Once the optimal architectures have been identified, we also perform physical optics simulations with the MAOS[9] package to generate full point-spread functions (PSFs). Methods and results from both are presented below.

3.1 KEBS Simulations

The KEBS tool was use to run a 4-dimensional grid of simulations over the following parameters:

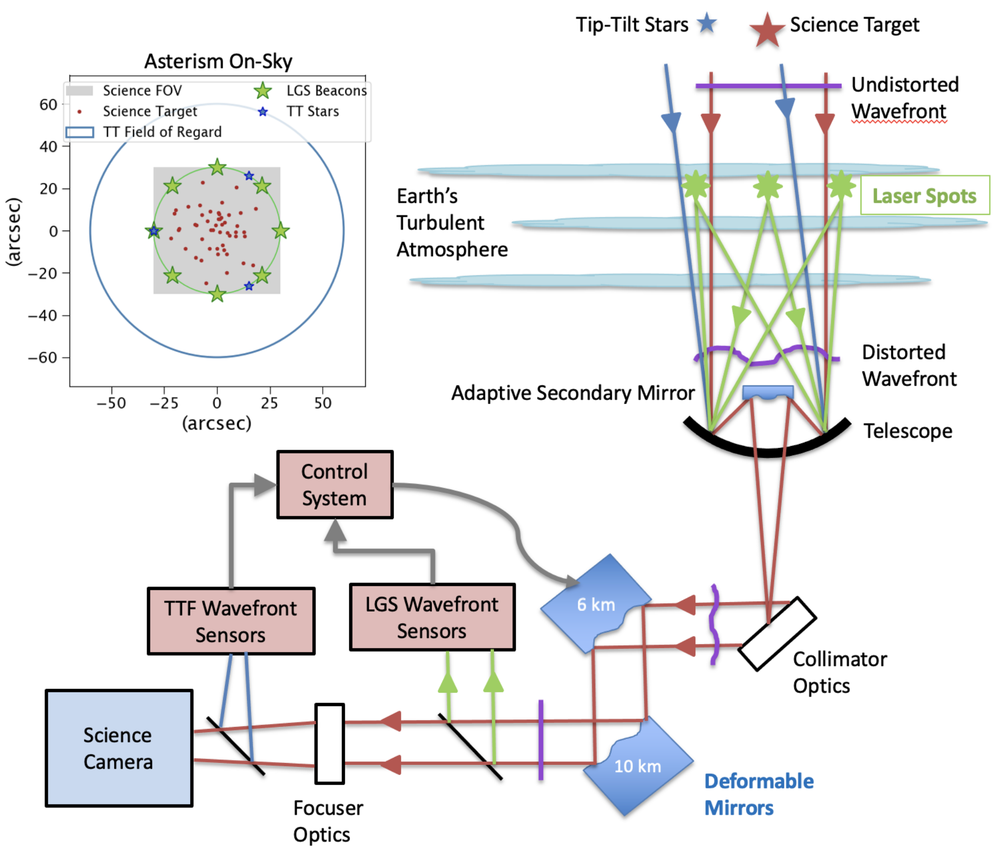

Figure 4 - Notional schematic of the KOLA multi-conjugate adaptive optics system. The adaptive secondary mirror will serve as the ground-conjugate (-100 m) and two additional DMs will correct turbulence at 6 km and 10 km. The inset figures shows the LGS and NGS asterism with 3 NGS WFS for tip-tilt-focus correction and 6 or more LGS beacons used to sense high-order aberrations. The number of laser beacons and acutator counts on each DM are currently being explored in trade studies.

1. LGS beacon count - range: 4-12, increment=1
2. LGS power per beacon - 20W + range: 30-60W, increment 5W
3. ASM actuator count - range: 1600 - 4000, increment 200; range: 4500 - 6000, increment 500
4. Loop rate - range: 1000 - 2400, increment 200; range: 2800 - 4000, increment 400

For each simulation in the grid, the total, low-order, and high-order WFE were recorded as well as the Strehl, FWHM, and ensquared energy at 50 mas for the u, g', r', i', Y, J, H, and K filters. Simulation results were interpolated onto a denser grid for plotting purposes. Example results in the r' (620 nm) filter are shown in Figure 5 for different actuator counts and number of LGS beacons for a fixed loop rate of 1600 Hz and power per beacon of 50W. Regions of optimal performance are identified as those that fall within 5% or 10% of the peak performance and are shown as contours in the results figures.

KEBS simulations were run at 30 deg zenith angle in median Mauna Kea seeing conditions ($r_o = 16$ cm, $L_o = 50$ m). The NGS were located at 30" radius for the field center and set as V=14 mag, K-type stars. TTF sensing was performed at 1 μm and the high-order and TT sensing and correction loops run at the same rate. Shack-Hartmann wavefront sensors were used in all cases. Additional error terms were included for uncorrectable static telescope aberrations (39 nm), uncorrectable dynamic telescope aberrations (29 nm), uncorrectable instrument aberrations (5 nm), static WFS zero-point calibration errors (25 nm), dynamic WFS zero-point calibration errors (20 nm), residual sodium layer focus changes (34 nm), and DM hysteresis (13 nm), DM-to-lenslet misregistration (15 nm), DM-to-lenslet pupil scale errors (15 nm), and a high-order WFE margin of 24 nm.

Note that in the KEBS simulations for KOLA, the tomographic errors tend to dominate above 200W of LGS power, 6 LGS beacons, and 3000 actuators. This is apparent when results are displayed for simulations run with fixed total laser power and varying the beacon count and actuator count (Figure 6). The tomographic model has not yet been extensively validated on sky.

3.1.1 KEBS Results

We identify a feasible optimum for the system architecture with the following parameters:

- ASM actuator count = 4000
- Number of LGS beacons = 8
- Power per beacon = 50 W, Total Power = 400 W

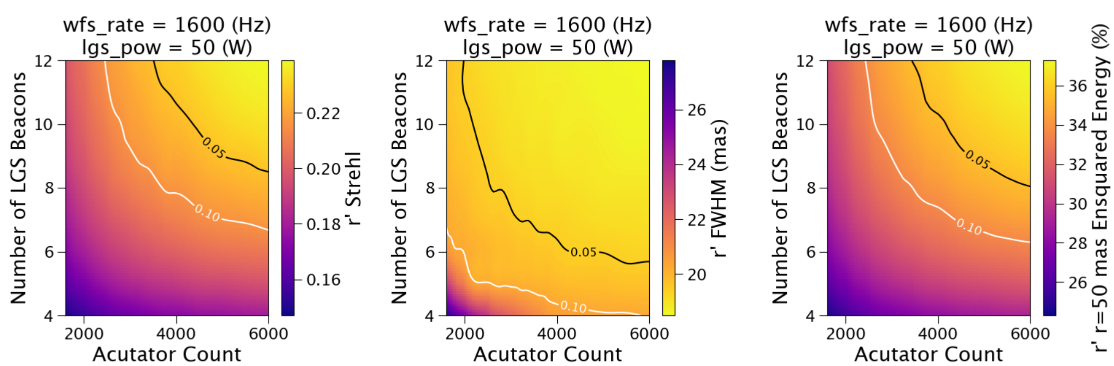

Figure 5 Image quality metrics derived from Keck Error Budget Spreadsheet showing Strehl (*left*), FWHM (*middle*), and the ensquared energy in a 50 mas box (*right*) in the r' filter. As expected, performance increases with more laser beacons (with fixed power per beacon and thus increasing total laser power) and more actuators on the ASM.

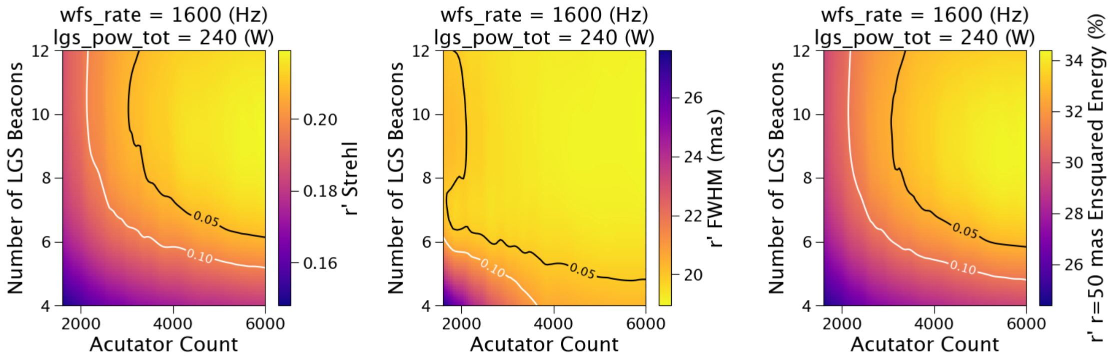

Figure 6 Image quality metrics derived from Keck Error Budget Spreadsheet showing Strehl (*left*), FWHM (*middle*), and the ensquared energy in a 50 mas box (*right*) in the r' filter. Total laser power is fixed to 240W and the loop rate is 1600 Hz. There are clear performance advantages to increasing the number of LGS beacons up to at least 8, indicating that tomographic error is important.

- Loop rate = 1600 Hz

The delivered image quality of such a system at r' would be S=0.22, FWHM = 19 mas, and an EE_{50mas} = 34% (Figure 7. While the spatial resolution does not quite meet the requirements, the KEBS simulations have significant additional blurring terms imposed to match the current Keck AO system. The MAOS simulations below may give a more accurate prediction of the resulting image quality metrics and actual PSFs.

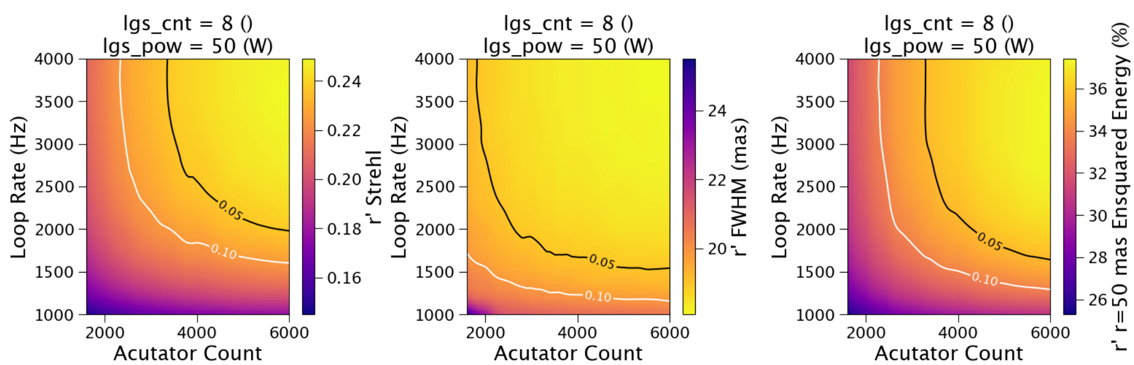

Figure 7 Image quality metrics derived from Keck Error Budget Spreadsheet showing Strehl (*left*), FWHM (*middle*), and the ensquared energy in a 50 mas box (*right*) in the r' filter. LGS beacon count is fixed to 8 with 50 W per beacon. The metrics show a moderate 10% reduction in Strehl and ensquared energy by adopting 4000 actuators and a loop rate of ∼1500 Hz.

We note that the total LGS power may be reduced if the loop rate can be increased in order to reduce total hardware costs. Similarly, the actuator count could be downgraded to as low as 2600; however, significantly more laser power (and number of beacons) would be needed to maintain performance and the incremental cost of additional laser far exceeds the incremental cost of adding actuators.

3.2 MAOS Simulations

We setup MAOS simulations with the optimal KOLA system parameters identified in the section above. Simulations included 8 LGS beacons (side-launched) and an associated WFS for each beacon, three deformable mirrors, and three infrared tip-tilt-focus (TTF) WFS. The first deformable mirror is an adaptive secondary mirror (ASM) with 4000 actuators conjugate to -100 m and an inter-actuator spacing of 15.4 cm on the primary. Two additional downstream DMs (conjugate to 6km and 10km) each have ∼3370 actuators with a spacing equivalent to 16.8 cm on the Keck primary, which is similar to that of the ALPAO Keck HAKA DM. The LGS constellation contains 8 sodium LGS beacons, ∼7 magnitude each (50 W beacon), that create spots at 90 km on a circle with a 30" radius. The LGS asterism is illustrated in Figure 4 along with the position of the NGS stars used for TTF and LBWFS correction and the science target. The LGS WFS hhave sub-aperture sizes matched to the ASM actuator spacing and the WFS detector characteristics (readnoise, diffusion, number of pixels per subaperture, etc.) are significantly improved over the existing Keck LGS WFS. The tip-tilt-focus sensor operates at infrared wavelengths, similar to TRICK on the current Keck I AO system. The wavefront sensor integration time is 1/1600 seconds and the duration of each simulation is 1 second.

Compared with the current Keck AO system, we assume a number of other improvements. The actuator strokes are increased from 2 μm to 30 μm for the ASM and 7 μm for the DM6 and DM10. The interactuator stroke is also improved from 1.2 μm to 2.0 μm for all three DMs. The high-order WFS is improved with lower readnoise (from 3 e- to 0.5 e-), reduced pixel size (3" to 0.5"), increased number of pixels per sub-aperture (4 to 25), and smaller misregistration errors (15% to 5% per subaperture). As a baseline, we also assume significant improvements in the telescope-induced aberrations and vibrations and NCPA (i.e. we drop the *surf* and *wspsd* MAOS parameters).

3.2.1 MAOS Results

MAOS results are in broad agreement with KEBS, delivering Strehls of 12% at g', 21% at r', 53% at Y, and 87% at K bands on axis (Figure 8. The spatial resolution as expressed by an empirical FWHM improves from 44 mas at K band to 17 mas at r'.

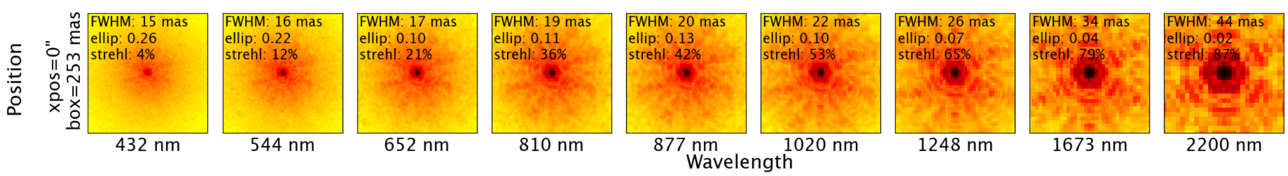

Figure 8 PSFs for different wavelengths from MAOS simulations with 4000 actuators, 8 LGS beacons, 50W per beacon, running at 1600 Hz loop rate. The displayed PSFs are at the center of the LGS and NGS constellation (i.e. R=0").

Despite the low Strehl at wavelengths shorter than r' (650 nm), there is still significant light concentration in u and g' bands when compared to seeing-limited observations. Figure 9 shows the radius of 50% and 80% ensquared energy for different wavelengths and even the shortest wavelength filters give $r_{EE50} < 50$ mas and $r_{EE80} < 100$ mas.

The performance over the science field of view (30" in radius, 60" in diameter) is shown in Figure 11 and the corresponding PSFs in the r' are shown in Figure 10. Performance is largely flat out to R=20" in all filters and rapidly degrades in the blue filters further out.

4. CONCLUSION

We conclude that reaching near-diffraction-limited performance at visible and infrared wavelengths over a moderate (60" diameter) science field and with high sky-coverage is feasible with a multi-conjugate AO system on the Keck telescopes. This system, named KOLA, would contain a 4000 actuator ASM, 2 additional high-altitude DMs, at least 8 LGS beacons with 50W each, and 3 TTF sensors. All performance simulations were conducted under median Maunakea seeing conditions at 30 deg zenith angle and with 3 tip-tilt-focus NGS located 30" from the field center and with V=14 mag. These are fairly typical conditions for fields in the Milky Way disk, bulge, or Galactic Center.

The delivered image resolution and quality would be comparable to the infrared AO systems planned for the first-generation ELT AO systems. The science enabled by KOLA will be extensive, including Solar System

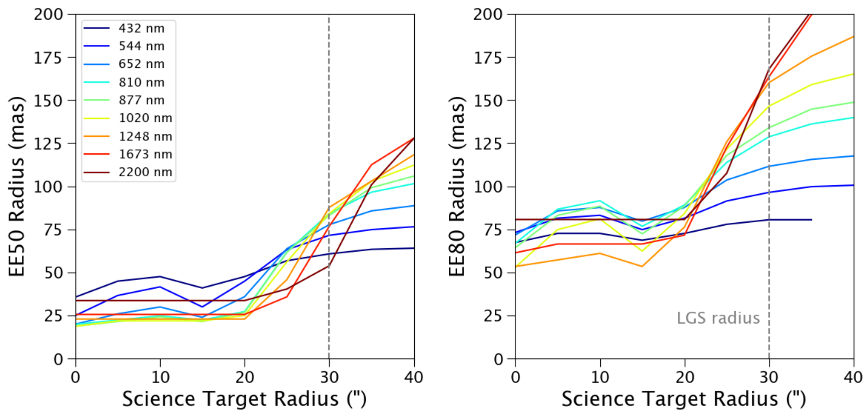

Figure 9 Radii with ensquared energies of 50% (*left*) and 80% (*right*) from MAOS simulations for 4000 actuators, 8 LGS beacons, 50W per beacon, running at 1600 Hz loop rate. Metrics were measured on MAOS PSFs at different wavelengths (*color*) and field positions (*Science Target Radius*).

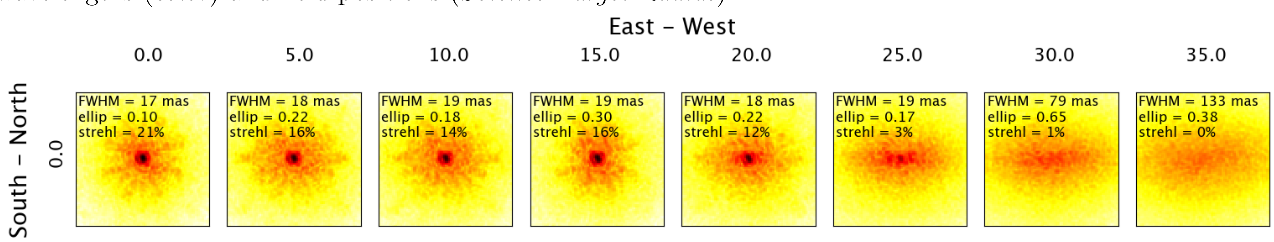

Figure 10 PSFs for different science target field positions from MAOS simulations with 4000 actuators, 8 LGS beacons, 50W per beacon, running at 1600 Hz loop rate. The displayed PSFs are from the r'-band filter.

and exoplanets science, the fundamental astrophysics of black holes and neutron stars, and galaxy evolution and cosmology. KOLA will be complimentary to the planned ELTs, comparable to JWST, exceed the spatial resolution of HST.

In addition to the KEBS trade studies shown above, further trade studies are being performed with MAOS to explore the LGS beacon count and power, the actuator count and altitude of the high-order DMs. These trades will inform the preliminary design of KOLA and allow for cost estimation. We are also performing simulations for different NGS magnitudes and separations and estimating sky coverage metrics for different architectures. These more detailed results will be presented in Peck et al., in prep.

Based on comparisons between KEBS and MAOS, the largest differences come about due to (1) the tomographic error term and (2) unknown sources (and calibration) of static aberrations from the telescope or AO system. To address (1) requires an on-sky tomographic system, ideally on Maunakea, to estimate turbulence distributions and statistics and validate the error budgets and simulations. To address (2) requires a dedicated campaign at Keck to characterize and possibly correct sources of static, quasi-static, and dynamic aberrations from both jitter and high-order terms.

Finally, the cost of a KOLA system has not yet been factored into the optimization and trade studies described above. The number of wavefront sensors and lasers dramatically influences the cost using current off-the-shelf technologies. However, CMOS-based WFS cameras offer a significantly cheaper alternative that should be explored. The use of an ASM is also a significant cost driver for KOLA and may complicate the calibration and testing of KOLA. However, the ASM enables a large range of other types of AO correction for enhanced seeing to existing instruments, improved fiber coupling and throughput to precision radial velocity spectrographs, and future sensitive mid-infrared instruments.

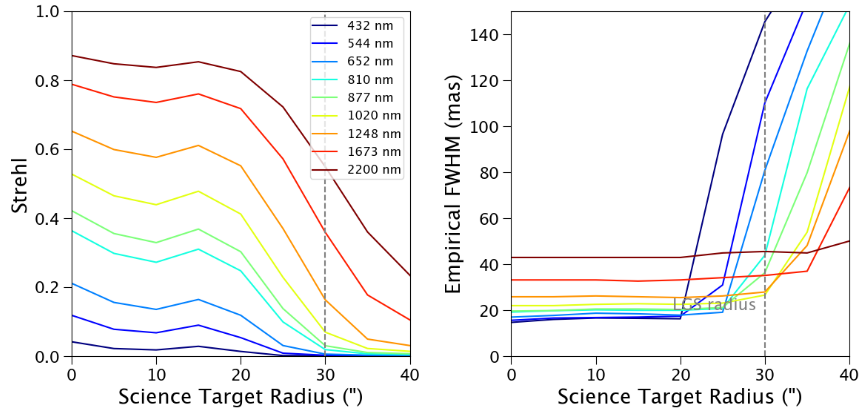

Figure 11 Strehl and empirical FWHM measured on MAOS PSF from simulations with 4000 actuators, 8 LGS beacons, 50W per beacon, running at 1600 Hz loop rate. Metrics were measured on MAOS PSFs at different wavelengths (*color*) and field positions (*Science Target Radius*).

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