PATHFINDERS TO EXTREMELY LARGE TELESCOPE ADAPTIVE OPTICS AT W. M. KECK OBSERVATORY

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Abstract. The Keck II LGS AO system is extremely productive scientifically. The lessons learned from this AO system, and the AO development activities currently underway and planned for the Keck telescopes, offer excellent opportunities for pathfinders to ELT AO.

1. Introduction

What ELT AO pathfinder roles should and can AO on 10-m telescopes play? The answer, from this author's perspective, is on-sky experience in three areas:

- *Quantitative Understanding of On-sky AO Performance and What Limits Performance*. This includes the performance of the overall system, the components, the telescope with AO, the science instruments and the science product where the product is the accuracy of photometry, astrometry, kinematics, etc.
- *Implementation and On-sky Demonstration of New Technologies and Techniques.* ELT AO will be challenging and anything that can be demonstrated and understood first on smaller telescopes will be time well spent. Techniques include operations models and tools.
- *Hands-on AO Expertise.* Experience is important for the development, implementation, optimization, and scientific use of ELT AO systems. Astronomers with AO observing and science product experience are needed to support and help define ELT AO. The astronomy community also needs to be ready to produce science with ELT AO. They need to develop their expertise to understand what science can be done, how to plan and carry out the observations, and how to reduce the data to science.

The W. M. Keck Observatory (WMKO) is continuing to improve the AO capabilities available on its two 10-m diameter telescopes. During this time mutually beneficial synergies with ELT AO projects have been sought and several successful collaborations have been developed.

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The current Keck II LGS AO system offers opportunities to gain the quantitative understanding discussed in the first bullet above, as well as, to develop the science expertise of the third bullet (as illustrated in sect. 2). The science performance limitations of the existing Keck LGS AO system has driven WMKO in the development directions discussed in sect. 3; these are very well aligned with the ELT AO needs to demonstrate new technologies and techniques. The WMKO development activities and their scientific benefits are briefly discussed in sect. 4.

2. Keck LGS AO Science Performance and Limitations

Since sky coverage will be critical for ELT AO this section focuses on LGS AO science experience and demand, as well as science performance and the limitations to this performance.

2.1. Science Productivity

In order to understand LGS AO science performance a base of LGS AO science experience is needed. WMKO has this experience with 124 refereed science papers based on LGS AO observations through late 2011. The number of refereed papers published worldwide based on LGS AO data is shown in Fig. 1. The Keck II system [1] has been responsible for 75% of the LGS AO refereed science papers published between 2004 and 2010.

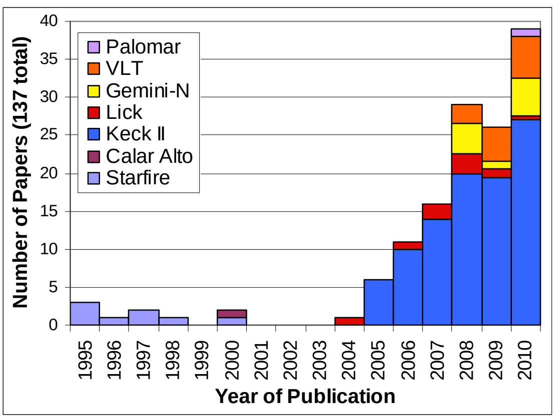

Fig. 1. Number of refereed LGS AO science papers published per year

The science being done using AO has changed with LGS at WMKO as illustrated in Fig. 2. For example, 48% of the LGS AO papers in this period were extragalactic versus 11% of all the NGS AO papers. The demand for AO on the Keck II telescope has been high with ~45% of the science nights assigned to AO between 2006 and 2010; about 2/3rds of these nights are LGS.

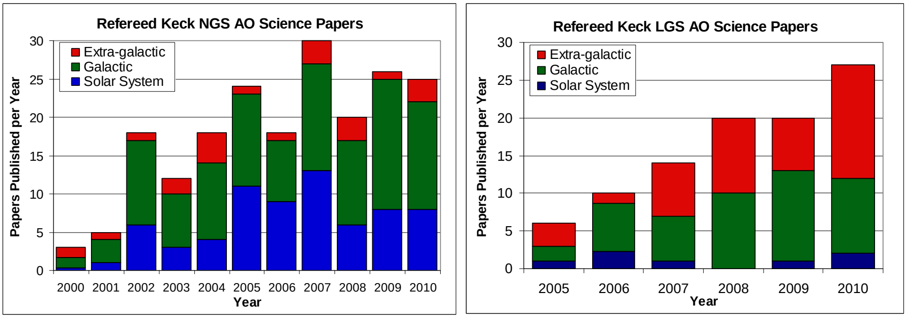

Fig. 2. Types of science being published using Keck II NGS (left) and LGS (right) AO.

2.2. Science Performance

The current Keck II AO performance is illustrated with a plot of K-band Strehl ratio (SR) versus the R-band magnitude of the tip-tilt star in Fig. 3. AO corrected star images from the science camera are shown for reference.

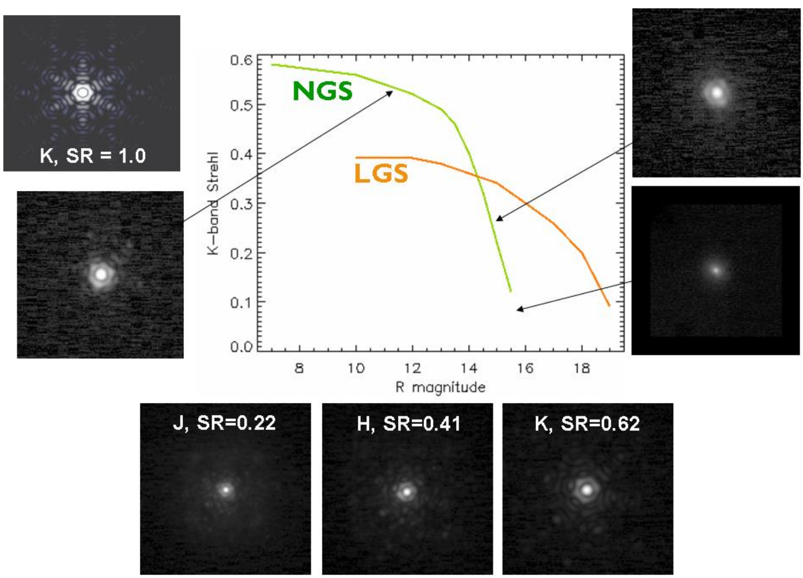

Fig. 3. Keck II AO performance as illustrated by a plot and images of K-band Strehl versus R-magnitude of the natural guide star, and by images of the natural guide star at different wavelengths [2].

Fig. 3 is an incomplete indicator of what to expect on a particular science program. We will therefore now look at the quantitative performance for two specific science cases. The first of these science cases is a survey of field brown dwarfs performed by M. Liu of the University of Hawaii between 2005 and 2007 [3]. Liu's plots of K-band Strehl and full-width-half-maximum (FWHM) are reproduced in Fig. 4. This survey was performed to find low mass binaries in order to use their measured orbits to determine the component masses.

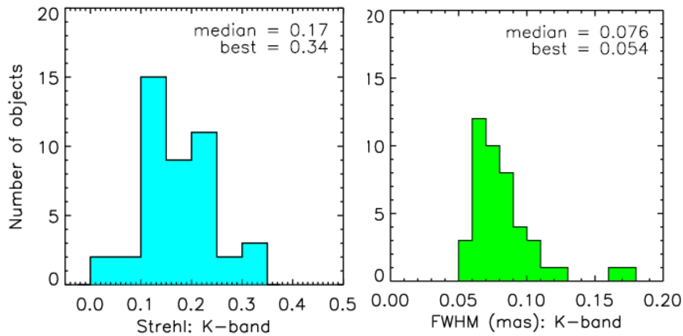

Fig. 4. K-band Strehl and FWHM from a Keck LGS AO survey of field brown dwarfs by Liu [3]. No data was discarded. The data includes a mix of seeing conditions and off-axis tip-tilt star properties.

It is important to note that a factor of 2 improvement in the accuracy of the relative positional errors of the orbital components would result in a factor of 6 improvement in the accuracy of the mass determinations. The relative positional and photometric errors are found to scale with the measured Strehl ratio and FWHM for the observation, as are seen in the case of the 2MASS 1534-2952AB low mass binary [4] in Fig. 6. The largest terms in the error budget for this science case are bandwidth and measurement errors due to both tip-tilt and higher order correction.

The second science case considered here is the Galactic Center. Ghez et al. used Keck LGS AO to measure the orbits of stars around the supermassive black hole at the center of our galaxy [5,6]. These measurements are currently limited to 0.17 mas in positional error and 17 km/s in radial velocities. The accuracy of these measurements is limited by source confusion in this very crowded stellar region.

3. Development Directions

3.1. Directions Driven by Science Limitations

In section 2.2 we found that that the positional and photometric accuracy of the low mass binary measurements were limited by the quality of the AO corrected images, especially Strehl ratio and FWHM. For the Galactic Center case the limitation is source confusion, which is also reduced with improved Strehl and FWHM. The largest terms in the wavefront error budget for these science cases are tip-tilt and higher order bandwidth and measurement errors. Good quantitative knowledge of the point spread function would allow for a reduction in source confusion for both of these science cases.

These limitations have driven the direction of our near-term development activities:

- Center launched lasers to reduce the perspective elongation in order to reduce the higher order measurement errors.
- Improved lasers to increase the return flux from the sodium layer in order to reduce the higher order measurement and bandwidth errors.
- Near-IR tip-tilt sensing to take advantage of the partially corrected AO images in order to reduce the tip-tilt residual errors.
- PSF reconstruction to reduce the source confusion.

We have also completed the preliminary design for a next generation AO (NGAO) facility that has been driven by a number of key science projects including understanding the formation and evolution of today's galaxies since z = 3, measuring dark matter in our Galaxy and beyond, testing the theory of general relativity in the Galactic Center, understanding the formation of planetary systems around nearby stars, and exploring the origins of our solar system. These science requirements have resulted in a number of key new science capabilities including near diffraction-limited performance in the near-IR (K-band Strehl ~80%), AO correction at red wavelengths down to 0.7 μm, increased sky coverage, improved angular resolution, sensitivity and contrast, improved photometric and astrometric accuracy, and imaging and integral field spectroscopy capabilities.

3.2. Consistency with U.S. AO Roadmap

The U.S. roadmap for investment in AO was updated at the request of the National Science Foundation (NSF) in 2008 [7]. The report identified a number of high priority investment needs, shown in Table 1, to support U.S. astronomy and to be ready for ELT AO.

Table 1. High priority investment needs identified in the 2008 U.S. AO Roadmap [7].

Discipline	Element	Goal
Wavefront Sensing	LGS Beacons	Availability of robust, cost-effective LGS AO system lasers
	Tomographic Reconstruction	Validation of the tomographic wavefront sensing approaches to predicted small residual wavefront errors …
	Wavefront Sensor Design	Validation of robust, versatile wavefront sensors ... to maximize sky coverage and reduce laser costs
Wavefront Correction	High-Stroke DMs	Development of scalable, cost-effective deformable mirror technologies …
Calibration	PSF Estimation	Understanding of the delivered PSF in order to obtain very accurate relative photometry and astrometry
Human Resources	Education and Training	Creation of a new generation of experts …

The current Keck LGS AO development activities are in direct alignment with the Roadmap's high priority investment needs. Improved lasers and launch facilities are in alignment with

LGS beacons. The near-IR tip-tilt sensor supports the wavefront sensor design priority. WMKO's PSF estimation activities are exactly those defined as a priority. Furthermore all of WMKO's AO development activities educate and train engineers and astronomers in AO technology, implementation, and science usage. The NGAO project is consistent with all of the high priority needs and will demonstrate the techniques and science that are the goals of ELT AO systems, including the TMT first light AO system, NFIRAOS.

4. Keck LGS AO Development Activities

In the following sections we briefly discuss each of the near-term Keck LGS AO development activities and what they will offer to the WMKO astronomical community. WMKO's NGAO facility is described elsewhere [8].

4.1. Laser Launch Facilities

The existing Keck II LGS AO system utilizes a launch telescope mounted on the side of the Keck telescope resulting in significant perspective elongation of the LGS beacon used for wavefront sensing. The Keck I LGS AO system currently being implemented will use a compact reflective launch telescope located behind the secondary mirror of the Keck telescope. The Keck II LGS AO system is also being upgraded with a center launch telescope. Both the Keck I and II launch facilities require beam transport systems. In the case of the Keck I system where the laser is located on the Nasmyth platform the beam transport system must utilize two tracking mirrors to get the beam onto the elevation moving part of the telescope. In the Keck II case the beam transport system only needs to take the laser from the dye amplifier table on the elevation ring of the telescope to the launch telescope.

4.2. Lasers

The existing Keck II LGS AO system utilizes a ~15 W pulsed dye laser. A ~25 W mode-locked continuous wave (CW) sum frequency solid state laser produced by Lockheed Martin Coherent Technology (LMCT) has been installed on the Nasmyth platform of the Keck I telescope. We have been working with ESO and TMT, as well as, other U.S. observatories, to produce a CW laser that will meet the needs of the next generation AO systems on large and extremely large telescopes. The result is a 20W Raman fiber laser, with back-pumping, under development by TOPTICA and MPBC [9]. At WMKO we are planning to procure one of these lasers to replace the existing Keck II laser. The sodium return per Watt for the LMCT and TOPTICA lasers is 1.5 and 10 times more, respectively, than the Keck II dye laser.

The predicted Strehl ratio improvement with the new Keck II center launch and laser, from a Monte Carlo simulation, is shown in Fig. 5. The reduction of perspective elongation with the center projection of the laser and dramatically increased return flux from the sodium layer result in a dramatic reduction in the high order measurement and bandwidth errors. The reduced sensitivity to variations in the sodium abundance is reflected in the reduced scatter of the data points with the new laser.

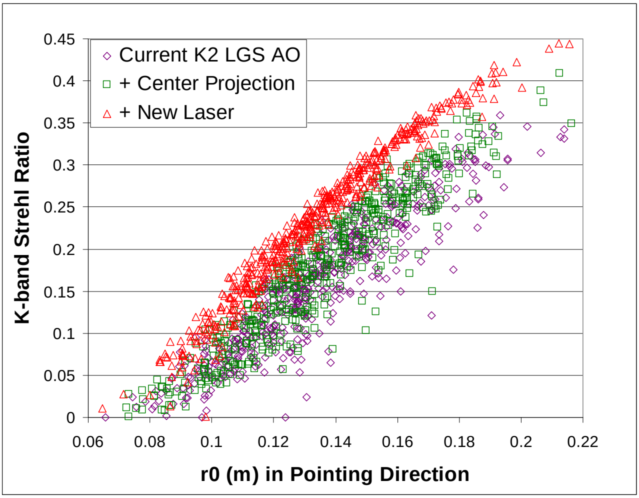

Fig. 5. K-band Strehl versus r0 for the current Keck II LGS AO system, for the Keck II system with center projection of the laser, and with the addition of the TOPTICA fiber laser.

The impact of this improved Strehl performance on the relative positional errors for the low mass binary case is shown in Fig. 6. Each improvement, center launch and new laser, results in a factor of 2 reduction in the positional error and hence a factor of 6 reduction in the accuracy of the mass determination.

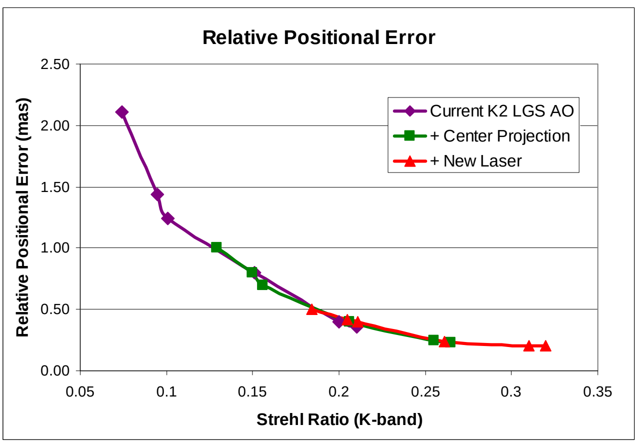

Fig. 6. Relative positional error versus K-band Strehl ratio for observations of the low mass binary 2MASS 1534-2952AB.

4.3. Near-IR Tip-Tilt Sensor

A near-IR tip-tilt sensor, based on a Hawaii-2RG detector, is currently in the detailed design phase and is expected to be implemented on the Keck I telescope in 2013. Tip-tilt sensing will be done on the AO-corrected core. Dichroics will be used to send the Ks-band or H-band light, over a 100 arcsec diameter field, to the sensor. When using Ks-band light the sky fraction over which the 1-D rms tip-tilt error is less than 20 mas will be increased from 45% to 75%.

4.4. PSF Estimation

Two efforts toward PSF estimation are currently ongoing. One for reconstructing the NGS AO PSF based on wavefront sensor telemetry [10] and a second to estimate the PSF as a function of field position based on atmospheric profiler data [11]. The former is a collaboration between L. Jolissaint, Gemini, University of Groningen and WMKO. The latter is a W. M. Keck Foundation funded project led by A. Ghez at UCLA in collaboration with the Optical Sciences Company and WMKO.

5. Conclusion

WMKO's development activities represent excellent pathfinders for ELT AO.

Acknowledgements: The development activities discussed here are the product of many people, especially the AO team at WMKO. The near-IR tip-tilt sensor development is a collaboration with Caltech Optical Observatories (COO) and Microgate. The NGAO project has been a broad collaboration especially with COO and the University of California Santa Cruz AO team. The Keck II LGS and Keck I NGS AO systems were built with funds from the W. M. Keck Foundation and NASA. The NSF has funded multiple AO development activities including the Keck I laser (0100845), the Keck II center launch (AST-0923593), the near-IR tip-tilt sensor (AST-1007058), laser designs (AURA C66003A) and the NGAO preliminary design (AST-0133798).

6. References

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