Design and Performance of the Keck Angle Tracker

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ABSTRACT

The Keck Angle Tracker (KAT) is a key subsystem in the NASA-funded Keck Interferometer at the Keck Observatory on the summit of Mauna Kea in Hawaii. KAT, which has been in operation since the achievement of first fringes in March 2001, senses the tilt of the stellar wavefront for each of the beams from the interferometer telescopes and provides tilt error signals to fast tip/tilt mirrors for high-bandwidth, wavefront tilt correction. In addition, KAT passes low-bandwidth, desaturation offsets to the adaptive optics system of the Keck telescopes to correct for slow pointing drifts. We present an overview of the instrument design and recent performance of KAT in support of the V\textsuperscript{2} science and nulling observing modes of the Keck Interferometer.

Keywords: angle tracking, stellar interferometer, adaptive optics, infrared detectors

1. INTRODUCTION

The age-old drive to observe ever more distant and fainter astronomical objects with telescopes capable of revealing increasing detail about their structure and movements through the cosmos continues unabated in the 21st century. Stellar interferometers are but the latest tool in the arsenal of the astronomer to unlock the myriad of secrets of the observable universe. By combining the starlight from a distributed array of telescopes to form an interference pattern (viz., interference fringes), stellar interferometers can observe stars with unprecedented levels of angular resolution. Since the attainment of "first fringes" in March 2001, the twin 10-meter class Keck telescopes atop the extinct volcano of Mauna Kea in Hawaii have operated as an 85-meter array known as the Keck Interferometer.

To achieve these levels of detail, stellar interferometers levy a host of demanding technological and operational requirements for creating strong (i.e., high contrast) interference fringes. Among the most stringent is the requirement to maintain strict parallelism between the stellar beams at the point at which they are combined. Any static or dynamic wavefront tilt between the combined stellar beams in the interferometer will reduce the contrast or visibility of the detected interference fringes, thereby diminishing the capability of the interferometer to accurately measure minute details of stellar objects. These differential wavefront tilts may be caused by telescope mispointing, the diurnal rotation of the earth, atmospheric turbulence, internal seeing effects, instrument vibration, or misalignment of the optics.

To maintain precise and identical pointing of each of the telescopes in the array as they track a target star as it moves across the sky, interferometers must both sense and correct the relative tilt of the stellar beams. Typically, specialized cameras known as star trackers sense the wavefront tilts and provide error signals to fast tip/tilt mirrors to zero out the relative tilts in real time. The Keck Angle Tracker, or KAT, is one such realization of a star tracker operating in the near infrared for the Keck Interferometer.

2. OPTICAL DESIGN

The primary science spectral bandpass for the Keck Interferometer is centered at 10 microns (N band) and extends in wavelength from about 8 microns to 12 microns. This passband is chosen because it offers the most favorable contrast ratio for detecting extrasolar planets. However, KAT operates primarily in J-band (at a center
wavelength of 1.25 μm) and occasionally at H-band (1.65 μm), but with reduced sensitivity in the latter since most of this band is reserved for the fringe tracker. The advantage of tracking at J-band is that although the wavefront quality makes it unsuitable for interferometry, it has higher flux levels than at N-band (10 μm) for tracking on the central star. Wavefront tilts in each of the stellar beams will result in spatial displacements on the infrared focal plane array (FPA) of KAT. KAT measures these displacements from the zero point of a quad cell on the FPA. Each quad cell is boresighted along the optical axis for its corresponding telescope and thus any deviation of the centroid image from the center of the quad cell will be interpreted as an angular or pointing offset (Fig. 1). KAT passes the high-bandwidth pointing offsets to the fast tip/tilt mirrors for high-bandwidth correction of pointing offsets. Lower bandwidth offsets are passed to the adaptive optics (AO) system of each of the Keck telescopes for keeping the fast tip/tilt mirrors centered well within their limited pointing range (viz., desaturation) in the presence of slow pointing drifts.

Figure 1. Quad cell detection scheme.

From the outset, KAT was designed to implement multiple-beam tracking for the entire telescope array of the Keck Interferometer with a single infrared camera. To achieve this, the concept of a “pseudo-pupil” was introduced to enable spatial separation of each of the telescope beams on the focal plane array while reducing the need for numerous oversized optics external to the camera. This helped to reduce costs by relying on mostly commercial off-the-shelf optics with only a moderate increase in optical complexity. As shown in the following schematic (Fig. 2), a pickoff mirror directs a compressed, collimated beam from the each of the Keck telescopes into the KAT primary mirror with a distinct tilt angle. For a particular beam, this will reimage the stellar target at a different position on the focal plane array. Thus, each telescope beam possesses its own unique quad cell for tracking.

Figure 2. Stellar imaging for the individual telescopes.

However, the tilt angles of the pickoff mirrors are not arbitrarily set. These angles are chosen so that the chief rays of all the telescope beams intersect at a single point along the optical axis in front of the KAT primary mirror. This intersection point defines the location of the pseudo-pupil whereas the beam footprints of all the combined beams define the pseudo-pupil’s spatial extent (Figs. 2 and 3). The precise location of the pseudo-pupil is itself determined by the spatial arrangement of the pickoff mirrors and the distribution of the quad cells on the focal plane array to minimize optical aberrations and beam confusion. With this arrangement, the secondary mirror can reimage the pseudo-pupil near the optical window of the KAT camera to yield a minimum beam footprint, thereby allowing reasonably sized optics to be used for both the dewar window and the detector lens.
3. OPTO-MECHANICAL LAYOUT

To support the nulling mode of the interferometer, the pupil of each of the Keck telescopes is split into a primary and secondary beam which is compressed and sent to the KAT switchyard dichroics via the fast tip/tilt mirrors. These dichroic beamsplitters then relay light in the wavelength passband of 0.8-1.7 μm (R, I, J, and H bands) through a bank of shutters and iris diaphragms to the KAT pickoff mirrors (Figs. 4 and 5).

Figure 3. Pseudo-pupil reimaging.

Figure 4. Functional opto-mechanical layout.
Next, the primary mirror (an f/3 paraboloid) and a convex spherical secondary mirror reimage and overlap the beams before directing them to the DCR (differential chromatic refraction) prisms. As illustrated in the following plot (Fig. 6), due to the spectral separation between the primary science band (N band) and the nominal angle tracking band (J band), the deviation between the atmospheric angles of arrival of the two bands will increase for target stars observed at greater zenith angles.

Figure 5. Opto-mechanical model and layout of KAT.

Figure 6. Wavelength dependence of differential chromatic refraction with respect to N band.
The DCR prisms, which consist of a pair of counter-rotating wedges (viz., a Risley prism), is designed to compensate for this angular deviation by offsetting the angle of the J-band light so that it points to the center of its quad cell when the science beam is tracking parallel to the optical axis of the interferometer.

Once past the DCR prisms, a shutter, and a pair of neutral density filters (for observing bright stellar sources), the beams propagate to the window of the KAT dewar (Fig. 7). The cryogenic dewar consists of a double vessel for liquid nitrogen, dual radiation shields, and a cold plate upon which is mounted a 6-position filter wheel, an apochromatic triplet lens, and a translation slide/mount for the Rockwell 1024x1024-format HgCdTe HAWAII FPA (Fig. 8). KAT only employs a single 256x256 quadrant of the HAWAII array.

The spot size (i.e., the FWHM of the PSF) of the stellar image on the FPA is not constant due to the variability of seeing conditions on the Mauna Kea summit. At a wavelength of 1.25 μm, the atmospheric coherence diameter $r_0$ ranges from 1.07 m at zenith for excellent seeing conditions to 0.16 m under poor conditions at a zenith angle of 65°. The short-exposure PSF of the atmosphere-telescope combination is comprised of a diffraction-limited core (comparable in size to the PSF of the telescope alone) which is surrounded by a fainter and broader halo set by the size of the seeing disk.

Under good seeing conditions, the diffraction-limited core dominates and the effective pupil dimensions of the Keck telescopes determine the spot size. However, under poor seeing conditions, the spot size grows larger and is determined instead by the seeing disk. Nevertheless, since the AO system (which has 56-cm diameter subapertures in the Keck pupil) corrects higher-ordered Zernike modes of the atmospherically perturbed wavefronts, the diffraction-limited core in the Keck beams will generally dominate.

![Figure 7. The KAT cryogenic dewar.](image)
4. OPERATIONS

KAT is closely associated with the Tip/Tilt Metrology (TTM) subsystem which provides high-bandwidth wavefront tilt correction. The layout of the KAT/TTM control logic is given in the Figure 9. This system has a separate central processing unit (CPU) for KAT and the TTM. The KAT CPU generates tip/tilt error signals based on KAT images and feeds them to the TTM CPU through shared memory. The TTM CPU, which is connected to the fast tip/tilt (FTT) actuators, applies tip/tilt corrections to the optical beams. KAT sends desaturation targets to the AO system and the M7 mirrors through a CORBA/keyword Bridge and EPICS, while the TTM sends split actuation targets directly to the M14 mirrors through an interprocessor carrier board.

In addition, KAT gets fringe tracker pointing offsets through client tools. The Nuller and Telescope (azimuth) interface with KAT/TTM is presently not in use. The Hand Paddle tools add search capability for the KAT in acquiring targets. Both the Hand Paddle and AO Chop tools have access to the telemetry server through a CORBA interface and have some control capability through Client Tools. Each telescope employs a centroiding algorithm on a 16x16 pixel-wide subarray of the FPA during star acquisition and switches to quadrant detection on a 4x4 quad cell when tracking is locked. Software modes include search, semi-lock, and locked tracking and user interfaces include GUIs for display of real-time parameters such as spot size, relative strehl, and readout noise (Fig. 10).
Figure 9. KAT/TTM control logic.

Figure 10. KAT GUI for display of target images and real-time parameters.
5. PERFORMANCE

Routine closed-loop tracking at 10 Hz has been demonstrated on the summit with < 5 mas resolution for a 9-10 magnitude star in J-band (at a 100-Hz update rate). Limiting magnitudes are 14 in J-band and 6.5 in H-band with readout noise < 10 e\(^{-}\) and < 40 e\(^{-}\), respectively. Correction of differential chromatic refraction down to a zenith angle of 50° has been achieved with the DCR prisms. With a measured plate scale on the FPA of 36.7 mas/pixel, the rms residual angle tracking error is currently at 0.1 pixels. If \(\sigma_{\text{tilt}}\) is the total differential rms tilt error per axis in radians between any two combined science beams, the resultant visibility is given by\(^{14}\):

\[
V = \exp \left\{ -1.23 \left( D \sigma_{\text{tilt}} / \lambda \right)^2 \right\}
\]

Thus, the visibility loss due to differential tilt in K band (\(\lambda = 2.2 \mu m\)) for the fringe tracker (assuming uncorrelated tracking errors in both beams), is less than 2%.

6. SUMMARY

The Keck Angle Tracker has been installed and operational on the summit of Mauna Kea with optics, electronics, and a detector to support angle tracking for the Keck 1 and Keck 2 telescopes since early 2001 (Fig. 11). A Risley prism common to all the telescope beams is employed to correct for differential chromatic refraction at high zenith angles between J-band (the nominal angle tracking band) and the science bands (e.g., K and/or N). The dewar consists of a filter wheel, a triplet lens, and a Hawaii focal plane array mounted on a focusing stage. The camera electronics sit next to the dewar, grab frames from the detector, and pass the data to the KAT control software through a fiber optic link.

Figure 11. KAT in the beam-combining room of the Keck Observatory.

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