Performance and Verification of the Keck Interferometer Fringe Detection and Tracking System

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ABSTRACT

The fringe detection and tracking system of the Keck Interferometer, Fatcat, has be operational ever since first fringes at Keck, albeit not in full capacity; at present it supports single baseline (Keck-Keck) operations only. We briefly discuss the instrument design from a hardware and realtime controls standpoint. We also show some recent visibility data from the instrument and summarize Fatcat's limiting sensitivity. Finally, we will discuss near and longterm evolution of the instrument through planned upgrades and summarize avenues for enhanced capability.

Keywords: Stellar Interferometer, fringe tracking, group-delay tracking, Keck Interferometer, infrared detectors

1. INTRODUCTION

The Fatcat is designed to be a workhorse instrument; it allows phasing of the interferometer in all of its operational modes and collects scientific measurements for certain modes such as parametric imaging, differential phase and narrow-angle astrometry. The instrument essentially consists of six, two-way Michelson combiners, that are supported by three infrared cameras and associated electronics. The cameras and combiners are optically coupled via single-mode (SM), infrared fiber cables.

The instrument layout is highly modular and functionally allows fringe-tracking on up to six baselines simultaneously, with each camera servicing interferogram measurements on two combiners (or baselines). In actuality, Fatcat is required to provide tracking on a maximum of five baselines – these comprise five bootstrapped baselines that are minimal set necessary to phase-up a six telescope imaging array (two Kecks and four outriggers). If a single camera fails, tracking is still possible on four baselines.

Five of six Michelson combiners are optimized for near infrared (NIR) operation, i.e. in the astronomical H & K bands, and allow tracking in either or both bands at the same time. The sixth combiner operates in the astronomical K and L bands, and is also the primary conduit for inter-band differential phase observations, to be used in direct detection of Hot Jupiter type planets and other high sensitivity experiments. The NIR correlators are supported by two cameras based on Rockwell HAWAII focal plane arrays (FPAs). The third camera is optimized for mid-infrared (MIR) operation and uses a Rockwell MBE PICNIC FPA with a 5.0 μm cutoff wavelength. All cameras are housed in mid-sized, windowless, cryostats and use infrared single mode (SM) fibers to channel the combined light from the correlators to the cameras via cryogenic feedthroughs. The SM fibers act as spatial filters for the combined wavefront and limits the extraneous background to a single spatial mode. Each cryostat also contains four identical optical relays, and motorized wheels that house filters and prisms (and can house gratings). A final focal stage images up to four spots (two baselines, front and back side of the beamsplitter), either white light spots or spectra, onto the FPA.

The primary function of Fatcat is active fringe tracking on a baseline - it estimates the fringe position at a prescribed fast rate and compensates for fringe motion by controlling a fast delay line. The fringe position is

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a statistical variable, obeying atmospheric tilt statistics of the wavefront impingent on the interferometer and requires sampling at a rate faster than the its coherence time τ_c. τ_c is expected to be around 10 ms on the Keck-Keck baseline, but may in fact be larger due to spatial averaging across the not insignificantly sized Keck apertures. At present, the fringe motion at Keck is dominated not by the atmosphere, but by acousto-mechanical sources of noise in the observatory environment. Besides fast tracking, Fatcat also supports cophasing on faint sources via longer integration times. In this mode, a majority of the atmosphere induced position error is removed via fast tracking on a nearby bright star thereby effectively synthesizing a larger coherence time for the faint object. Integration times are then limited by the degree of anisoplanatism. Finally, Fatcat data may be telemetered and recorded for scientific purposes. The is done at present for parametric imaging, and will be done for differential phase and narrow angle astrometry observations in the future. Table 1 summarizes the role FATCAT plays with regards to the major science modes of the Keck interferometer.

Table 1. Summary of major operational modes of the Keck interferometer and the role played by FATCAT in supporting that mode.

Science Mode	Science Instrument	Fatcat Role
Keck Parametric Imaging	Fatcat, at HKL bands	Fringe tracking, Science data
Differential Phase	Fatcat, at HK KL bands	Fringe Tracking, Science data
Nulling	Nulling interferometer and camera	Fringe Tracking, co-phasing
NA Astrometry	Fatcat	Fringe Tracking, co-phasing, Science data
Interferometric Imaging	Imager	Fringe Tracking, co-phasing

At this point in the draft, it is necessary to qualify that FATCAT in its current embodiment at Keck Observatory supports only a fraction of its full functionality. Just a third of the requisite hardware, two correlators and one camera, are actually installed at the summit. These are sufficient to support operations for single baseline Keck-Keck science and engineering tests being carried out at present. The remainder is used for laboratory testing at JPL and will be moved to the summit with the installation of the outrigger telescopes. The third Fatcat camera is still undergoing fabrication.

2. FRINGE TRACKER LAYOUT

The 25 mm compressed primary star beams are delayed in the continuous motion fast delay line carts and directed into the optical switchyard. A dichroic in the switchyard reflects H and K band light into the beam combiner, and transmits J band radiation to the stellar angle tracker. For dual star observations, the secondary star is similarly fed into a separate beam combiner. All optics and mounts of a single combiner are housed on a 61×122 cm^2 relocatable breadboard, positioned with the help of a kinematic mounting system. Each combiner has its own stimulus or artificial star that is mounted on a smaller 25×40 cm^2 mezzanine breadboard. The stimulus can generate a collimated white light beam, that is injected into the interferometer via a leaky dichroic. It also houses and allows injection of a solid state boresight laser (660 nm), and has provisions for injection of a He-Ne "constant term" (CT) metrology signal for i) monitoring AC fluctuations of the internal OPD or ii) measuring the DC constant term for narrow-angle astrometric observations.

Beam combination takes place at the main beamsplitter B1 with nearly 50-50 performance between the 1.5-2.5 μm science band, and a 30-70 performance in laser band around 630 nm. The combined beams from the complementary sides of B1 are coupled into SM fibers with optimized off-axis parabolas. The fibers act as spatial filters for the combined beam – translating dynamic wavefront errors into output intensity scintillation. Each fibers are approximately 2.5 m in length and terminates inside a fringe tracker cryostat, via a flange mounted cryogenic feedthrough. The fibers also limit extraneous thermal background radiation to a single spatial mode – in addition, the warm end of each fiber illuminates an annular off-axis parabola P2 or P3 which terminates on the emissive cold surface of a three-stage solid-state refrigerator, forming a sort of Lyot stop.

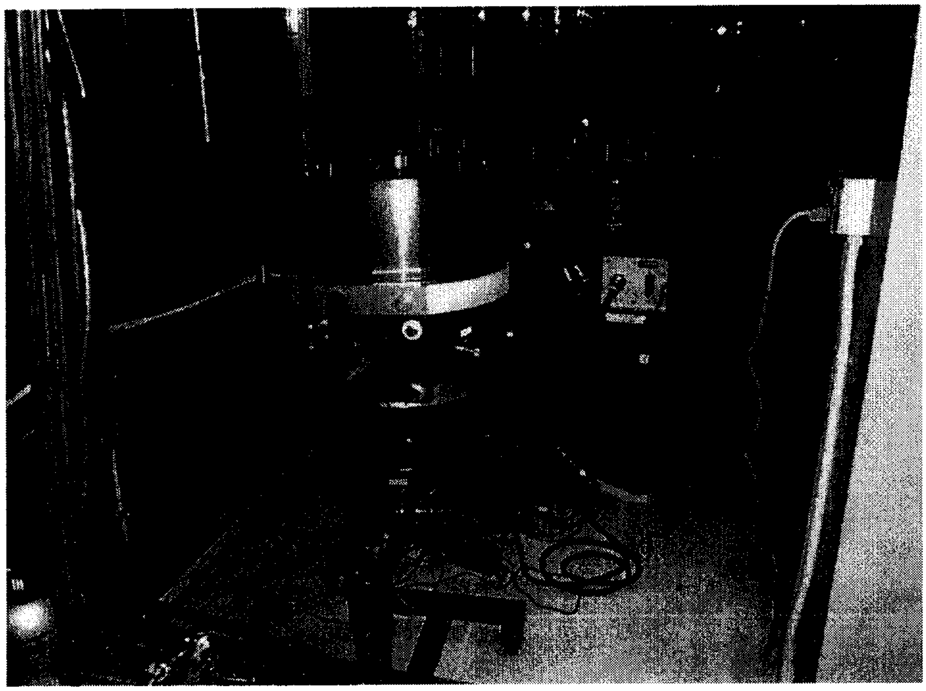

Figure 1. Photograph of an area of the beam combining laboratory in the Keck Observatory basement. In the foreground is the Fatcat camera II seen during a period of warm alignments. The beam combination table is towards the rear.

Within the windowless cryostat, each fiber output is recollimated to 19 mm with an achromat doublet and propagates along one of four identical optical relays. Each beam is bandpass filtered with filters selectable from five locations on a filter wheel. The beam may be dispersed with a low or medium ($R \sim 10^2$) dispersion direct view prism, corresponding to a $\sim$ 10 pixel spectrum on the FPA. Future upgrades to the cameras include adding higher dispersion $R \sim 10^3$ grisms, useful for interferometric studies of emission or absorption line features in sources. Both the filter and prism wheels of the camera are positioned with the help of externally mounted dc motors. A common imaging parabola focuses all four beams onto a cosmetically satisfactory region of the FPA. An undispersed beam forms the white light spot and is used for measurements of the WL interferogram. At present the optics allow up to 80 % of the encircled energy to fall on a single 18 μm pixel. A dispersed beam, imaged to a few pixel spectrum, is used for science measurements and allows realtime reconstruction of the group delay.

All three Fatcat cryostats use liquid nitrogen as cryogen. The LN_2 vessel in the inner vessel of the MIR cryostat is actually to be pumped to solid for lower (55 K) temperature operation. Closed cycle refrigerators were not considered out of the fear that a pistoning cold head would subject the sensitive optical system to intolerable levels of microdynamics. An autofill system with vacuum insulated transfer lines, not yet functional, is likely to ease the operational logistics of dealing with all six liquid cryogen based dewars that support the interferometer's day-to-day functioning.

The camera electronics are divided into local and remote electronics, linked by fast fiber communications (5 ns timing jitter). The remote electronics, resides close the camera and includes the video chain and pre-amplifiers, A2D converters, a clock distribution systems etc., standard equipment necessary for running a focal plane array. The local electronics are housed in a VME crate, and include a Motorola MVME-62 Single Board Computer running vxWorks. It also includes a camera card which features a large buffer for FPA clocking, accumulators for pixel co-adding, a dual port RAM for data acquisition, and modules for optical communication with the remote electronics. The camera card is responsible for storing raw clocks and generating the FPA clocking on arrival of hardware or software interrupts. Communication of the digitized pixel data back to camera card is

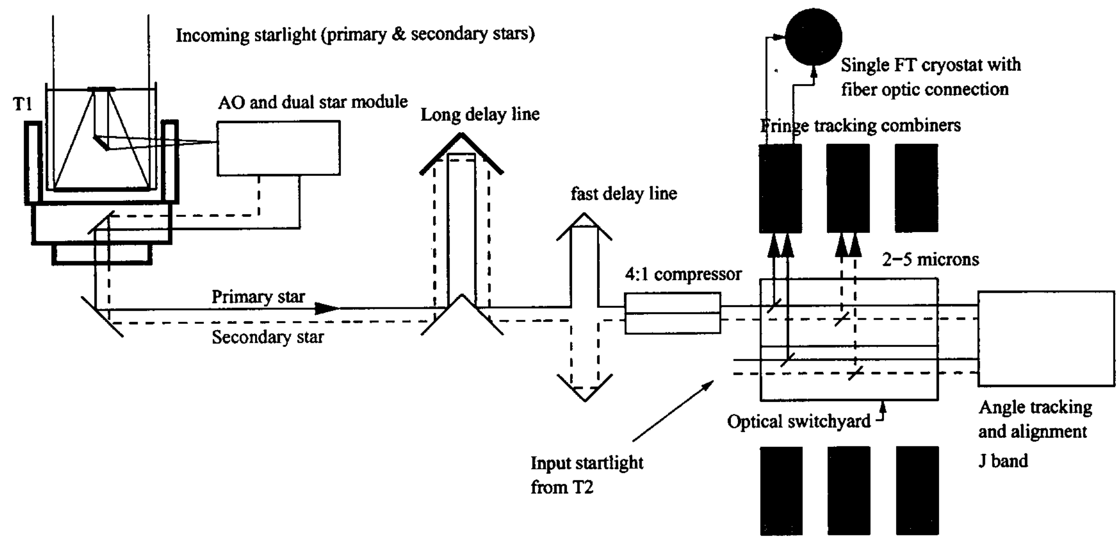

Figure 2. Schematic illustration of a single beamtrain at the Keck interferometer. Fatcat components are located towards right on both sides of the optical switchyard in one-inch beam space. Just a single Fatcat camera is shown. H & K bands are picked off by a dichroics in the switchyard for fringe tracking. J band and some visible is allowed to propagate on the angle tracking and auto-alignment purposes. CT metrology is injected near Fatcat and retroreflects off a corner cube in the DSM, monitoring OPD dynamics in the beamtrain.

handled by a gateway card housed with the remote electronics. The fast pixel read rate (1 MHz) and array slew rate (4-6 MHz) coupled the small number of pixels that must be read for interferometry allows fast frame rates (F_s, up to 2 kHz). Correlated double sampling along with multiple non-destructive reads allows very low noise operation. Fatcat achieves $\sigma_{CDS} \sim 5\ e^-$ with 64 non-destructive reads, which sets the detector noise floor as the dark current and background contributions at fast frame rates is negligible.

3. PATHLENGTH CONTROL AT KECK

Fatcat derives significant heritage from the NIR fringe tracker at the Palomar Testbed Interferometer (PTI; see Colavita et al. 1999), which used a NICMOS-III array for fringe detection. Fatcat has greater instrumental flexibility and is far more expansive in that it is designed to work on multiple baselines, but at its guts the instrument works in a manner similar to PTI. All tracking is consigned to H and K bands where Keck AO provides adequate performance (high Strehl ratios), while the isoplanatic patch size r_0 is well matched to the apertures of the 1.8 m outrigger telescopes. The fringe tracker measures the OPD between two arms of the interferometer at a rapid rate, and commands the delay line to compensate for the path difference. Delay line positioning itself is accomplished via local laser metrology sensing. Fringe phase information from a primary star may be used to co-phase a secondary star by applying the primary's phase as open loop feedforward corrections to the secondary star delay lines. Essentially background limited fringe detection of the secondary star should thus be possible.

The Fatcat camera is clocked at a programmable fundamental frame rate f_s, which can be as fast as 1 kHz. Raw Michelson phasors are measured over four bins via a calibrated, sawtooth shaped temporal modulation of the OPD with a delay line. All fringe tracker and delay line functionality is time synchronism through a timing distribution system that is linked to a 1 PPS derived from UTC. The amplitude of the modulation is approximately one wavelength, e.g. $\lambda_K \simeq 2.2\ \mu$m, and the stroke is implemented in one of the two delay lines of the two arms of the interferometer. Raw phasors are measured for both the white light and spectrometer, which usually correspond to the front and back side of the beamsplitter. The shape of the modulation allows phasors to be updated at a rate $5f_s$ in an overlapping manner, which reduces the mean data age and improves the fringe tracking servo performance. All raw phasors are calibrated and dewarped in order to correct for a wavelength to modulation mismatch. The phasors of the spectrometer may be stacked coherently, i.e., in reference to the white light phase, if averaging is required to build up signal-to-noise on the group delay. The delay line is servoed to a combination of the white light error and low-pass group delay, with group delay acting as a slower outer loop to execute fringe centering.

3.1. Internal Pathlength Control

Most optics in the Keck Interferometer beam trains are subject to vibrational excitation due to various and sundry machinery in regular use at the observatory. In fact the OPD fluctualtion are dominated by internal pathlength variations rather than the external atmosphere. Two active systems have been installed to help stabilize the internal OPD. These are the constant term laser metrology and the accelerometer feedforward systems.

The constant term (CT) laser metrology signal is injected into each Keck beamtrain via rugate filters from the vicinity of the fringe tracker. The CT propagates up the beamtrain to a retroreflecter in the dual star module. The CT samples beamtrain OPD 5 kHz, is AC coupled (1 Hz cutoff) and servos the delay line at high frequencies. At DC and low frequencies, the delay uses its own metrology as is required for positioning to sidereal targets. The CT servo has a 3 dB closed loop bandwidth of $f_c \simeq 180$ Hz and provides good rejection of disturbances in the 10-100 Hz range. The residual OPD in beamtrain with the CT on is about 70 nm rms.

Telescope and AO piston motions are monitored with bank of accelerometers mounted on the primary, secondary and tertiary mirrors on the Keck telescopes, and the AO and DSM benchs. The accelerometer outputs are doubly integrated, and signal conditioned. The resultant signals are digitized and summed with proper weights and applied to the delay lines as feedforward targets. Motions of the telescope optics and rigid body motions of the AO and DSM benches (located at the Keck Nasmyth platform) are monitored in this fashion.

3.2. Performance

The probability that a 2.0 μm photon incident on a Keck telescope is detected on the white light pixel by Fatcat is about 3 %, given the 0.8 duty cycle for detection. For low photon rates, tracking is limited by the detector read noise. The a system $V_s^2 \simeq 0.8$, and an unresolved target Fatcat requires about a 1.5×10^2 photons per frame to have sufficient signal-to-noise for tracking. This implies a limiting K magnitude of approximately $10.9 - 2.51 \log(500/f_s)$, where f_s is the fundamental frame rate. This limit applies at small zenith angle and is likely to degrade at lower elevations, and was estimated from observations of a K = 8.3 star. There is a caveat however, as this estimate make any assumption about performance of the AO at fainter magnitudes. Since the group delay estimator is considerably noisier, coherent averaging of the spectrometer phasors is used (8-16 samples for low photon rates) with a sliding boxcar filter.

Internal tests demonstrate that the 3 dB servo bandwidth of the tracker, with a simple integral controller and first order unwrapper, is about $\simeq f_s/11$. Currently, the tracker is being run at rates faster than are dictated by the atmosphere above Mauna Kea (at 0.5 to 1 kHz) so as to compensate for the considerable narrow band OPD noise due to vibrations in the beamtrain. Finally, the two point-aperture Greenwood frequency can be computed as $f_G = W/1.546 r_o = 11$ Hz, assuming $W = 20$ m/s as a constant wind speed. For a servo bandwidth of $f_c = 45$ Hz (for a 500 Hz frame rate) the residual fringe tracker error due to atmospheric motion is about $(f_G/f_c)^{5/6}$ or 0.3 rad rms.

For further details concerning the inclusion of grayscale and color images, consult the *Author Guide for Publication and Presentation* supplied to authors by SPIE or SPIE's web page on manuscript preparation.

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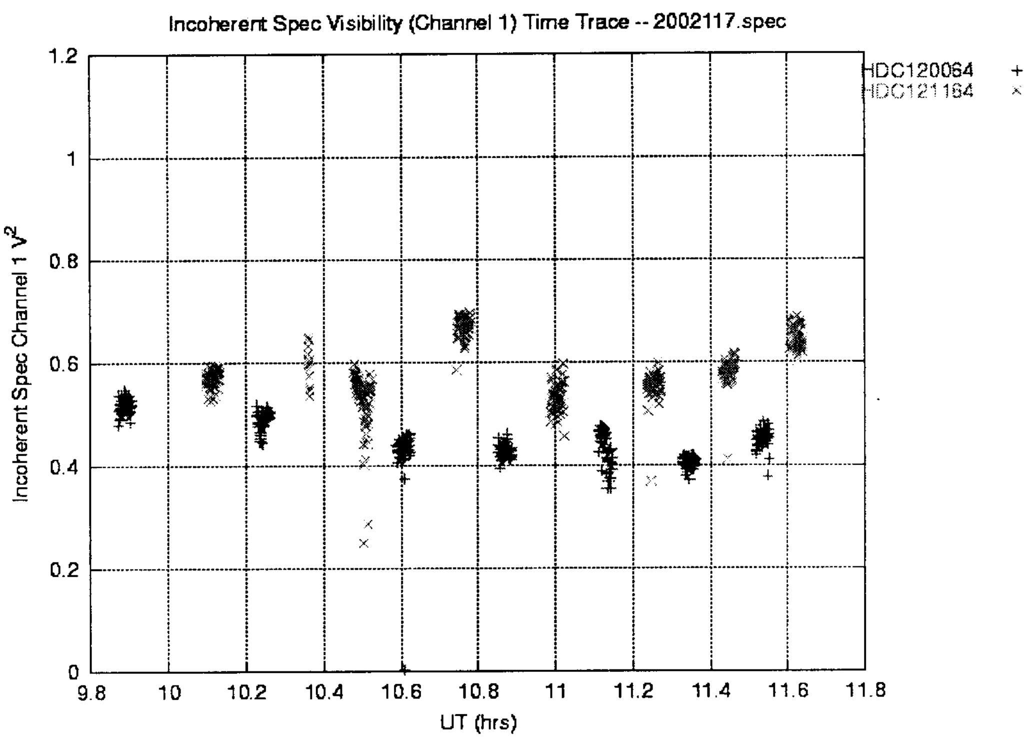

Figure 3. Processed incoherent spectrometer V^2 from data taken with the Kecks over two hours. Data are from a star switching experiment.

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