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Keck Interferometer: progress report

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ABSTRACT

The Keck Interferometer is a NASA-funded joint development between JPL and the W. M. Keck Observatory. The interferometer will combine the two 10-m Keck telescopes with four 1.8-m outrigger telescopes in several observing modes. These include: nulling interferometry at 10 μm to measure the quantity of exozodiacal emission around nearby stars; near-infrared differential-phase measurements to detect "hot Jupiters" by their direct emission; narrow-angle astrometry to search for exoplanets by their astrometric signature; and near-infrared imaging to address a variety of imaging science. Active development of the instrument subsystems and associated infrastructure is underway at JPL and CARA.

Keywords: Optical/IR interferometry; astrometry; nulling

1. INTRODUCTION

The Keck Interferometer is a NASA-funded joint project between JPL and CARA to interferometrically combine the two existing 10-m Keck Telescopes and four new 1.8-m outrigger telescopes[1,2]. Funding for the project began in October 1997 (fiscal year 1998) with funding from NASA's Origins program[3]. The Keck Interferometer is capable of a broad range of science, with its key science focusing on specific Origins topics. A schematic of the interferometer site at the summit of Mauna Kea, Hawaii, after installation of the outriggers, is shown in Figure 1.

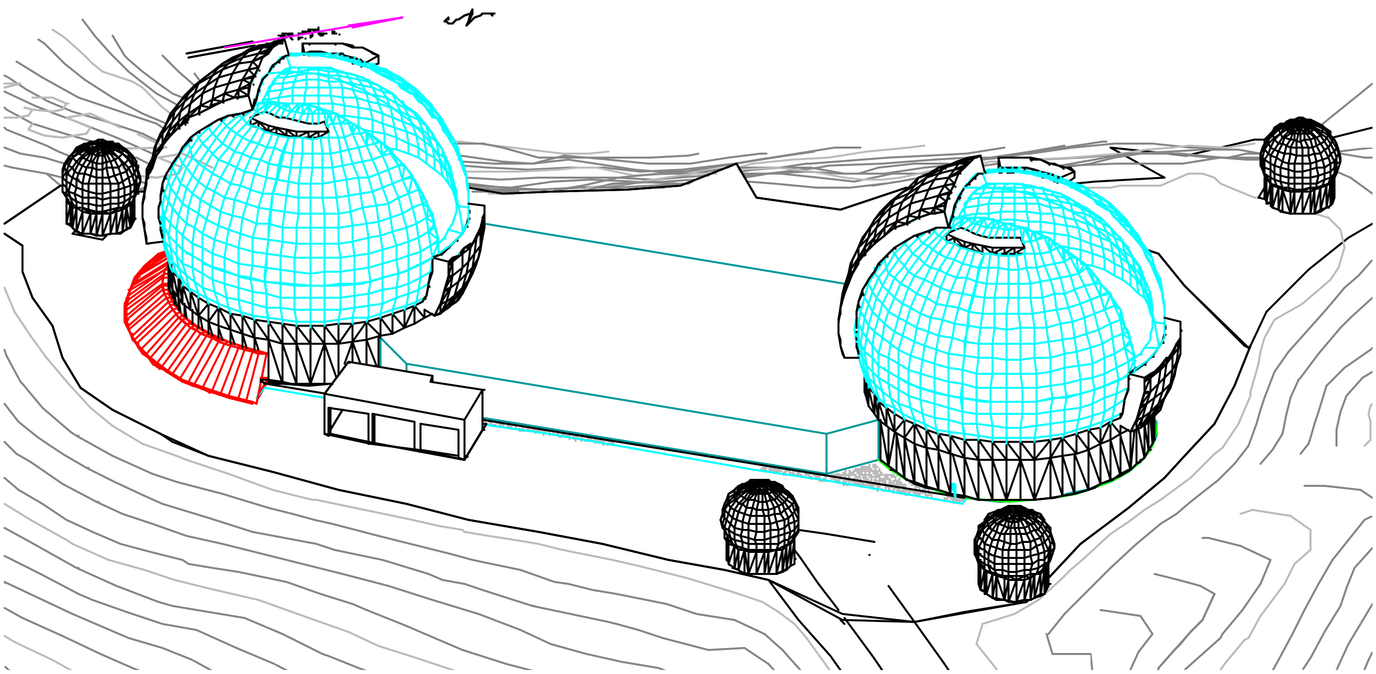

Figure 1: Schematic of the Keck Interferometer site as it would appear after installation of the outrigger telescopes.

The Keck Interferometer uses Michelson combination among the two Kecks and four outrigger telescopes. The two Kecks provide a baseline of 85 m in the NE direction. With the addition of the outriggers, a range of baselines from 30 m to 135 m is provided. For highest efficiency, all of the telescopes are phased: the Kecks use adaptive optics, while the outriggers will use fast tip/tilt correction. Cophasing among baselines is provided using active fringe tracking and active delay lines; for off-source cophasing, a dual-star feed will be installed at each telescope to bring the light from the source and a cophasing reference to the beam combining lab. The back-end science instruments of the interferometer include two-way combiners at 1.5-2.4 μm for astrometry, two-element imaging, and cophasing; a multi-way imaging combiner at 1.5-5 μm; and a nulling combiner at 10 μm.

2. SCIENCE WITH THE KECK INTERFEROMETER

Science with the two Kecks includes measurement of exozodiacal dust using nulling, detection of hot Jupiters using differential phase, and high sensitivity parametric imaging. Science with the outriggers and Kecks includes the astrometric search for exoplanets (outriggers only) and imaging with a 4, 5, or 6-element array.

1. Measurement of Exozodiacal Dust

The objective of the measurement is to characterize the exozodiacal emission around nearby stars. In addition to its intrinsic scientific merit, characterization of the dust disk will be used in planning for the NASA Terrestrial Planet Finder (TPF) mission.[4,5] The requirement is to detect a 10-solar-system equivalent zodiacal dust disk at a distance of 10 pc. The features of the problem that drive the measurement technique are the strong light from the central star and the relatively weak exozodiacal signal. However, as the disk is best detected in the mid-IR, the measurement technique needs to accommodate the strong 10 μm background. The approach uses interferometric nulling[6] to cancel light from the central star to reduce the required dynamic range, and fast modulation to accommodate the mid-IR background.

The scales of the problem match those of the instrument: at a distance of 10 pc, the diameter of the central star is ~1 mas, while the diameter of a (1 AU radius) dust disk is 200 mas; thus the light from the target will be collected in a single λ/D = 200 mas beam of a single Keck, while the interferometer resolution λ/B at 10 μm of 25 mas allows exploitation of high resolution methods. The measurement technique is shown schematically in Figure 2. Each Keck aperture is split into two halves, each of which is sent separately to the beam combining lab. Interferometer nullers[7,8] cancel most of the light from the central star on two 85-m baselines. The outputs of these nullers are then combined in a conventional beam combiner which uses fast fringe scanning to demodulate the exozodiacal signature in the presence of the 10 μm background.

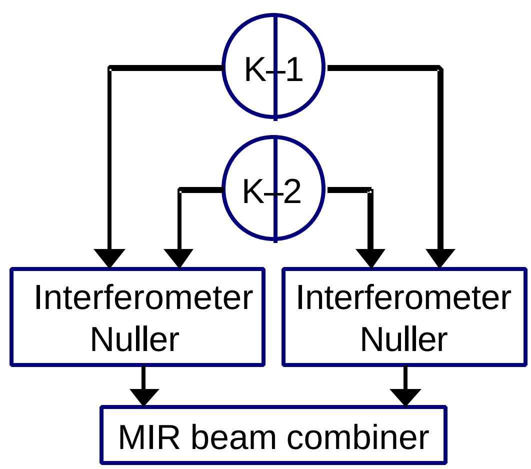

Figure 2: Schematic of nulling beam combination.

2. Detection of Hot Jupiters

The objective of the measurement is to detect warm Jovian planets from their direct infrared emission. It is a complementary approach to the high-precision radial-velocity technique[9] which first discovered these objects, and allows, for example, unambiguous mass determinations and validations of atmospheric models. The measurement is challenging because of the relative faintness of the planet vs. the star. However, with large telescopes, the signal-to-noise ratio is good, and the measurement technique must address primarily systematic errors. The approach (Figure 3) exploits the wavelength-dependent phase shift of the fringe position of the star-planet system: at longer wavelengths, the centroid of the star-planet system moves toward the cooler planet. Simultaneous measurements of the fringe phase at multiple wavelengths with a single beam combiner make many errors common mode. The multiple wavelengths are also used to calibrate residual temperature and water vapor turbulence feedthrough. More information on the technique, and the results of some preliminary experiments, are available elsewhere in this proceedings.[10]

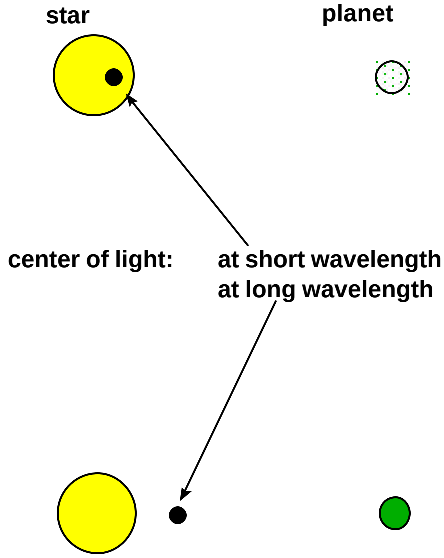

Figure 3: Differential phase measurement approach.

3. Astrometric Search for Exoplanets

The science objective is to search hundreds of nearby stars for planets to Uranus mass. The approach is high-accuracy narrow-angle astrometry,[11,12] implemented on the outrigger telescopes to allow for a long-term survey. The configuration of the interferometer for this measurement is shown in Figure 4, where the outriggers are configured to provide nearly orthogonal baselines, each ~100 m in length. Each outrigger is equipped with a dual-star feed to bring light from the target star as well as an astrometric reference star to the beam combining lab; end-to-end laser metrology monitors the interferometer optical paths. The requirement is to achieve an accuracy of 30 μas in an hour of integration time. Demonstration of differential astrometry has been one of the objectives of the Palomar Testbed Interferometer (PTI);[13] an update on PTI, and a discussion of recent astrometric results, is given elsewhere in this proceedings.[14]

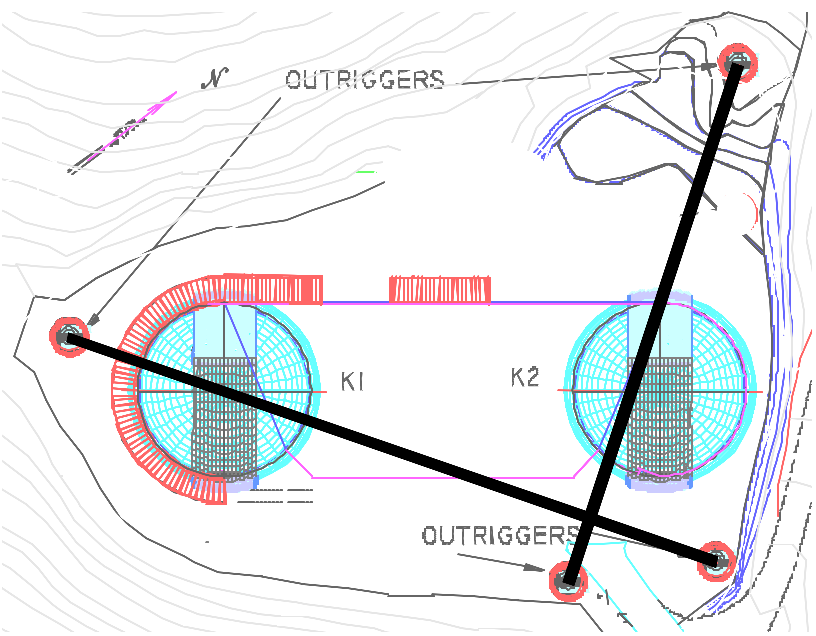

Figure 4: Astrometry configuration using the outriggers.

4. Interferometric imaging

With up to six elements available for imaging, the interferometer provides good (u,v) coverage. Significantly, 9 of the 15 available baselines include a 10-m telescope; in the background-limited regime, a baseline with a 10-m and 1.8-m telescope is equivalent to a pair of 4.4-m telescopes. The large telescopes are also exploited for cophasing, as shown in Figure 5. The cophasing geometry illustrated for the 5- and 6-telescope arrays provides the best limiting magnitude for tracking an off-axis cophasing source. The (u,v) coverage is illustrated in Figure 6. The range of baseline lengths available in imaging mode varies from 30 to 135 m, providing a maximum angular resolution of 3 mas at 2.2 μm. Cophased observations provide the highest sensitivity: in the 6-telescope configuration with 15 simultaneous science baselines, a Keck-outrigger baseline has a point-source sensitivity of K=19 for an SNR of 10 in 1000 seconds. Additional information is available in ref. 15.

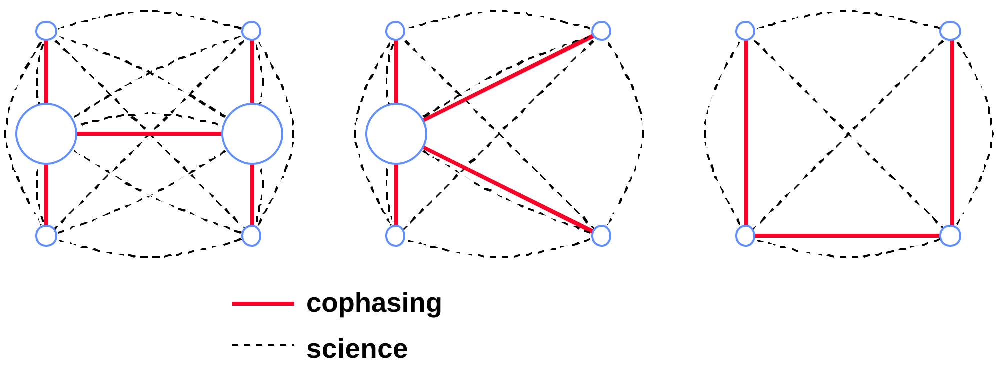

Figure 5: Cophasing and imaging with 4, 5, and 6 telescopes.

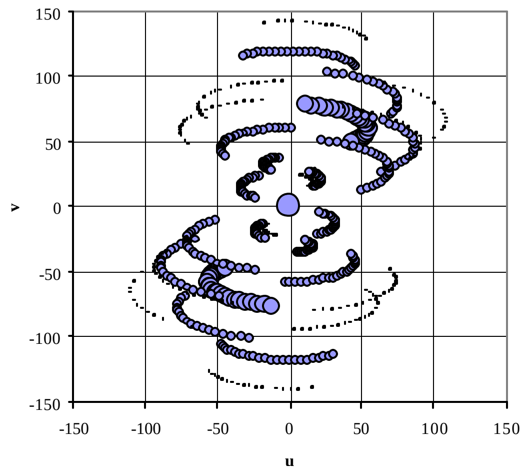

Figure 6: (u,v) coverage of the 6-element array. Hour angle coverage is +/- 4 hrs. Variable track widths are used in the figure to indicate the telescopes comprising each baseline.

3. INSTRUMENT UPDATE

The beam train of the interferometer is illustrated in Figure 7. The components are briefly described below.

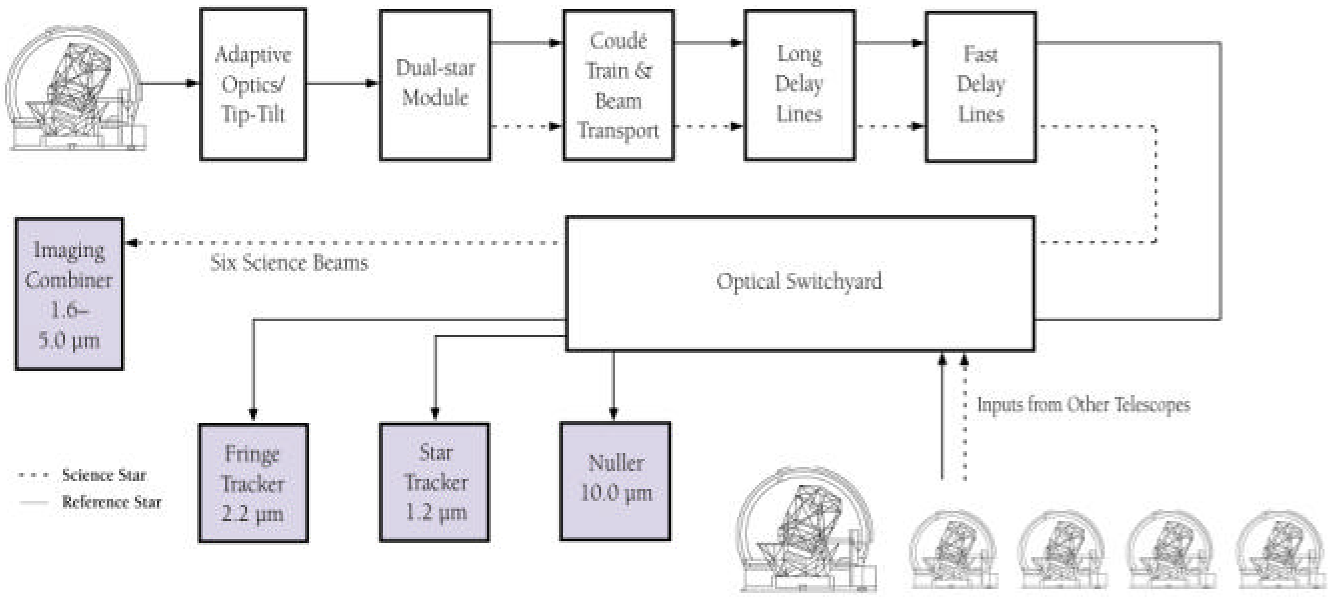

Figure 7: Keck Interferometer beam train.

1. Telescopes and Domes

The interferometer uses the two existing 10-m Keck telescopes plus 4 new 1.8-m outrigger telescopes. The outriggers are used with the Kecks for imaging, and separately for astrometry. Key specifications for the outriggers, in addition to those on wavefront quality and pointing in order to exploit the good seeing on Mauna Kea, include the requirement for a stable pivot to enable the astrometric measurements. The telescopes are being fabricated by EOS Technologies[16] in Tuscon, AZ. The telescopes use an f/1.5 ULE primary, and provide a system focal ratio of f/17 at the dual-star module. They incorporate a fast tip/tilt mechanism for wavefront control produced by Physik Instrumente. The domes are being fabricated by Electro Optics Systems[17] in Canberra, Australia (the parent company of EOST). They are 9-m diameter co-rotating enclosures employing a composite shell. The use of a co-rotating design allows for a lightweight but high strength design to survive worst case environmental loads. Schematics of the outrigger telescopes and domes are shown in Figure 8. Acceptance tests for the first telescope and dome are planned for later in 2000.

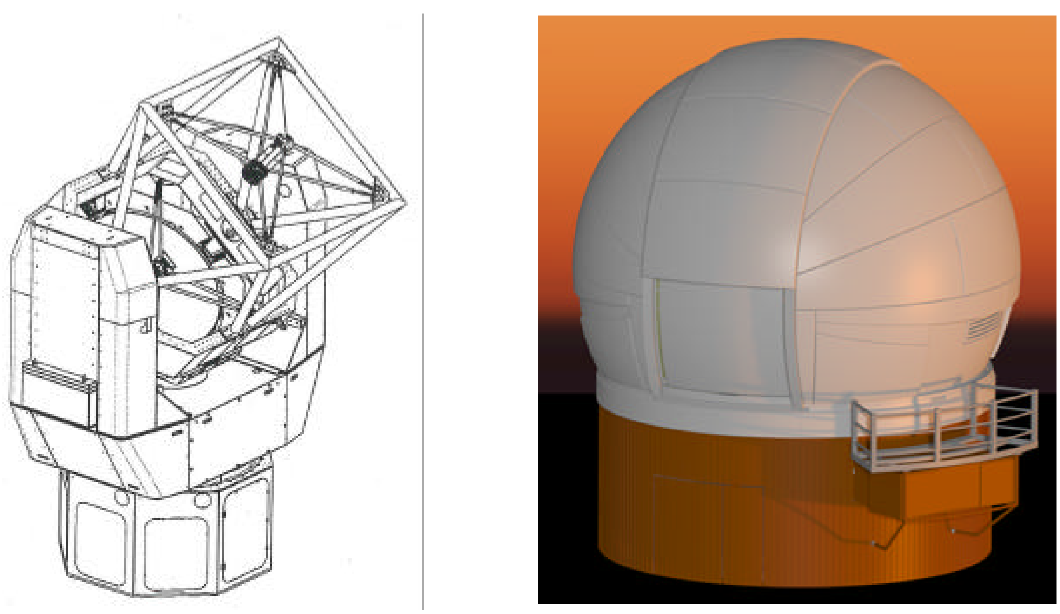

Figure 8: Schematic of outrigger telescope and dome.

First fringes with the interferometer will use siderostats, similar to those used at PTI. They are currently installed at the site adjacent to Keck 2; the siderostat shelters can be seen in the foreground in Figure 9.

Figure 9: Siderostat enclosures are visible in the lower right of the photo, in front of Keck 2.

2. Adaptive optics

CARA, with funding from the Keck Foundation, has deployed an adaptive optics system on Keck-2; as part of the interferometer project, a copy of this system (natural guide star only) is being built for Keck-1. The Keck-2 system had first light on Feb. 4, 1999, and is being regular scheduled for science. A summary of the Keck-2 AO system and some of the first science is presented elsewhere at this meeting.[18] For the outriggers, fast tip/tilt compensation is adequate for use in the near-IR, and the fast/tip tilt mirror described above is used with a tilt sensor in the beam combining lab.

3. Dual Star Module and coude

A dual-star module (DSM) is located at the Nasmyth focus of each telescope to enable cophasing by producing two collimated beams from two separate stars. The DSMs are similar in concept to those used at PTI.[13] Figure 10 illustrates the beam train from the Keck AO system through the Keck DSM for the bright star when the DSM is configured for imaging. The outrigger telescopes have similar DSMs located on their left elevation forks, similarly producing two collimated output beams.

Each DSM feeds light to a Keck or outrigger telescope coude train; a coude system for the Kecks was added as part of the interferometer project, while a coude system was specified for the outriggers. Of note is that while the coude system can be passive for one of the stars (say, the primary), the secondary star beam cannot be made coaxial with the telescope axes and so must be actively steered via M6 (on the telescope) and M7 (fixed at the base of the telescope).

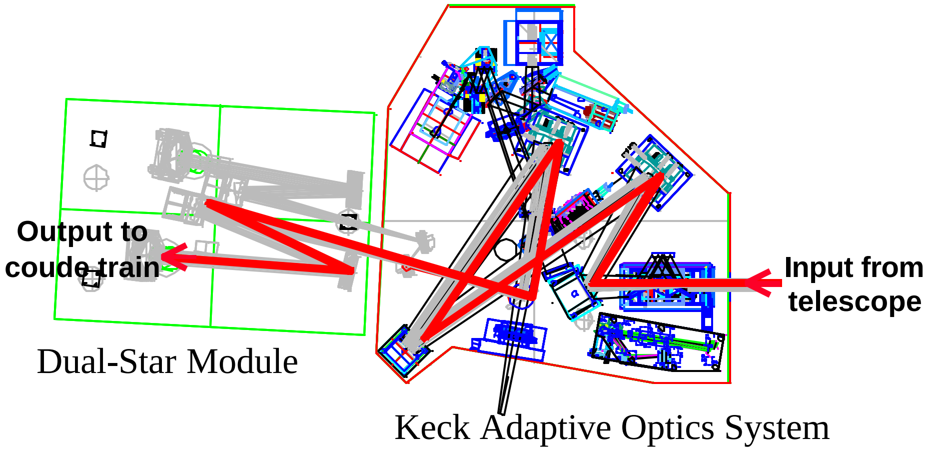

Figure 10: Keck dual-star module fed by the Keck AO system.

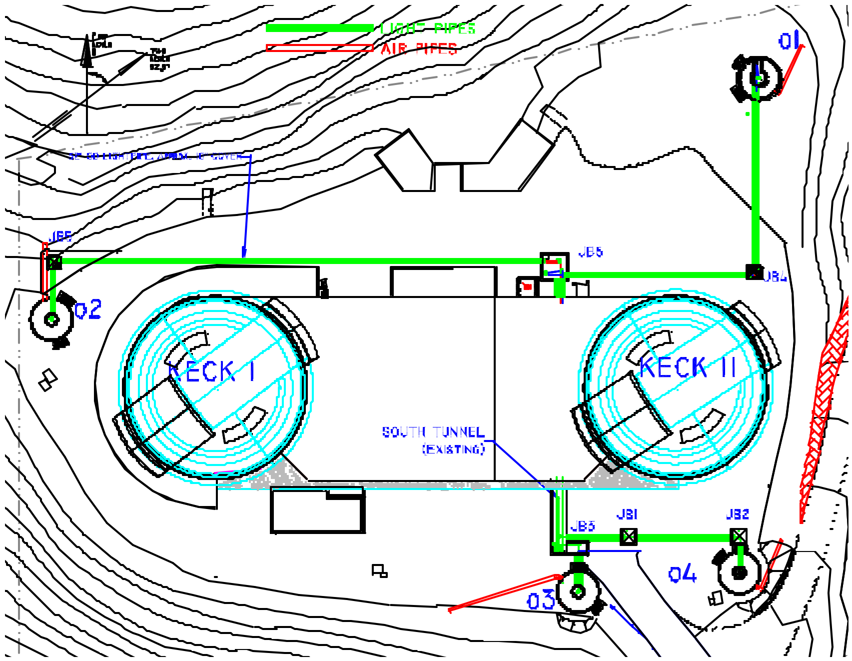

Figure 11: Plan view of the interferometer site.

4. Beam transport and beam combining lab

The beam transport system employs oversize flats which direct both the primary and secondary beams. The geometric compressed beam size is 10 cm for all telescopes, while the transport optics allow for a 15 cm unvignetted aperture for each beam to accommodate diffraction and alignment tolerances. Beam transport from the outriggers uses insulated underground beam pipes, as illustrated in Figure 11, while transport from the Kecks is through the coude tunnel which connects the two domes.

The beam transport system directs light to the beam combining lab, which is at the basement level adjacent to Keck 2. Figure 12 and Figure 13 illustrate the major subsystems in the beam combining lab; Figure 14 shows a photo of the beam combining lab during installation of the long delay line tracks. Attention has been given to controlling the thermal environment in the lab. As shown in the schematics and photograph, modular clean rooms partition the basement into separate areas for the long delay lines, the fast delay lines, and the beam-combining optics, providing a second layer of attenuation to environment disturbances, in addition to helping to maintain cleanliness of the optical system.

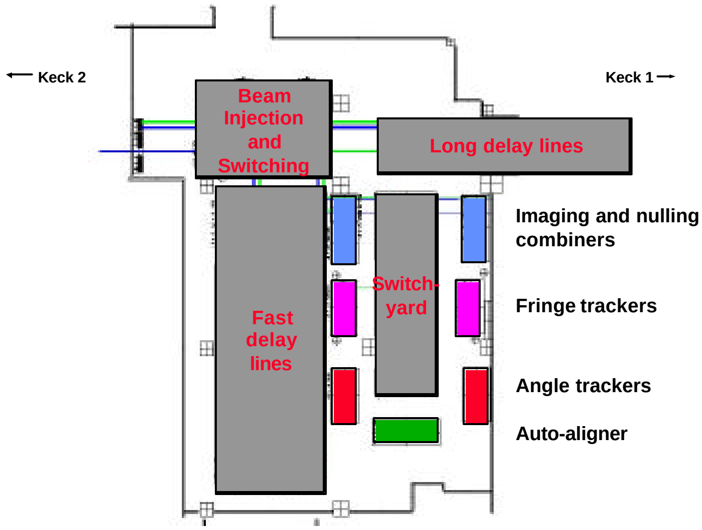

Figure 12: Schematic of the interferometer beam combining lab.

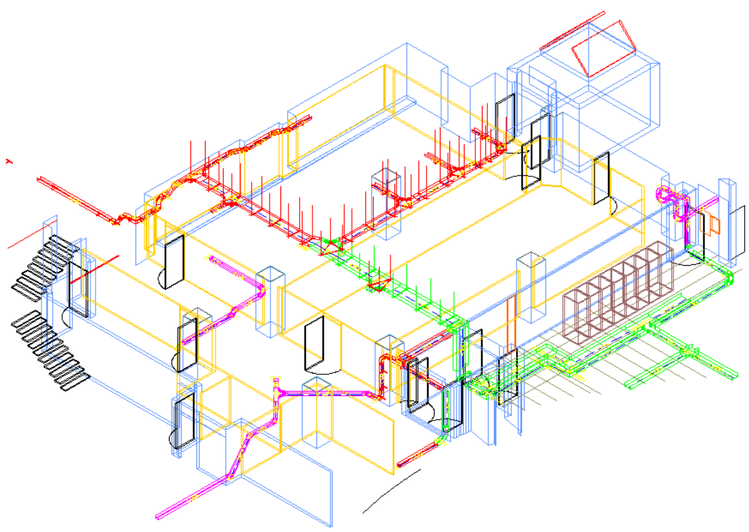

Figure 13: Isometric view of the beam combining lab.

Figure 14: Photograph of the beam combining lab during installation of the long delay line tracks (2/00).

5. Delay lines and Metrology

The light from the beam transport system is directed to the beam injection and switching optics, as shown in Figure 12, which feed the light into the long delay line system. The long delay system employs flat mirrors mounted on sleds which move along the coude tunnel in the basement. There is one sled per telescope, and each sled carries two 8"x14" mirrors. Each sled delays both the primary and secondary beams from that telescope by up to 170 m; the longer delays use a double pass through the delay line system. These are "move and clamp" delay lines, which are stationary during an observation and are only repositioned between targets.

After coarse delay by the long delay lines, the beam injection and switching optics direct the light into the fast delay lines. There is one fast delay per beam per telescope, for a total of 12, and these move along tracks in the beam combining lab as shown in Figure 12. Each delay line has a physical travel of 10 m, so that for a single baseline, a delay range of +/-20 m is available without moving the long delay lines. The delay lines are similar to the laser-monitored units used at PTI. They employ a four-stage servo design with a PZT, two voice coils, and a microstepped tractor motor, and provide full position and rate commanding. Figure 15 shows several fast delay lines being integrated in the laboratory at JPL.

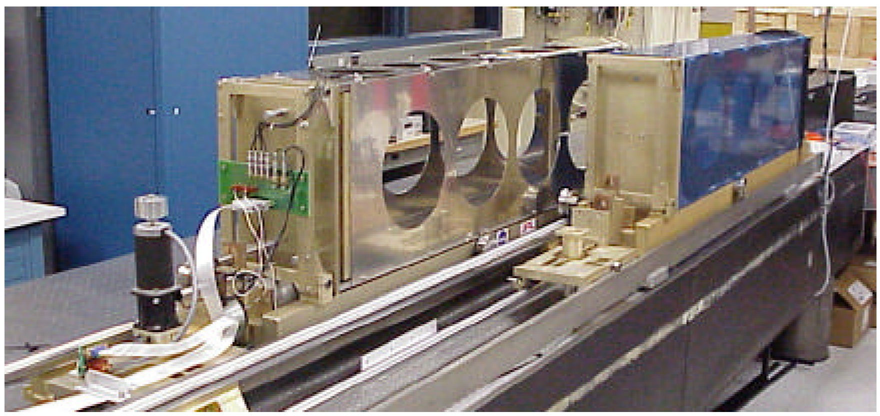

Figure 15: Fast delay lines in the lab at JPL.

The delay lines employ local laser metrology for real-time control of the servo systems. Again, this is similar to that used at PTI, except that the laser sources are fiber remoted to the control room to minimize heat dissipated in the beam combining lab. In addition, separate end-to-end laser metrology which monitors the entire optical system is implemented as required for narrow-angle astrometry and cophasing. This "constant term" metrology terminates at end points in the DSMs at each telescope. Optical path changes prior to the DSM are common to both the primary and secondary star, and so do not affect cophasing. If warranted, accelerometers could be used on those unmonitored optics to provide vibration attenuation through feedforward to the fast delay lines.

After exit from the fast delay lines, the 10-cm geometric pupils are compressed to 2.5 cm and directed to a switchyard table which directs light to the various starlight sensors.

6. Starlight sensors

Fringe Tracker Five 2-way H- and K-band Michelson beam combiners support the various observational modes of the interferometer. The foreoptics for each combiner are implemented on an optical breadboard. The output beams from two breadboards are fed via single-mode fluoride optical fibers to a 4-input near-IR camera. The camera uses one quadrant of a HAWAII infrared array with subarray readout to provide fast frame times. A schematic of the dewar, and a photograph of the first dewar during assembly, are shown in Figure 16. The array signal chain uses commercial video and clock buffer electronics with a custom second-generation clock generator and interface card to provide fast access for real-time use. Good array performance has been obtained with interferometer frame rates to 500 Hz. The use of post-combination single-mode fibers improves visibility calibration, yet allows the end-to-end laser metrology to use the same beamsplitter as is used by starlight.

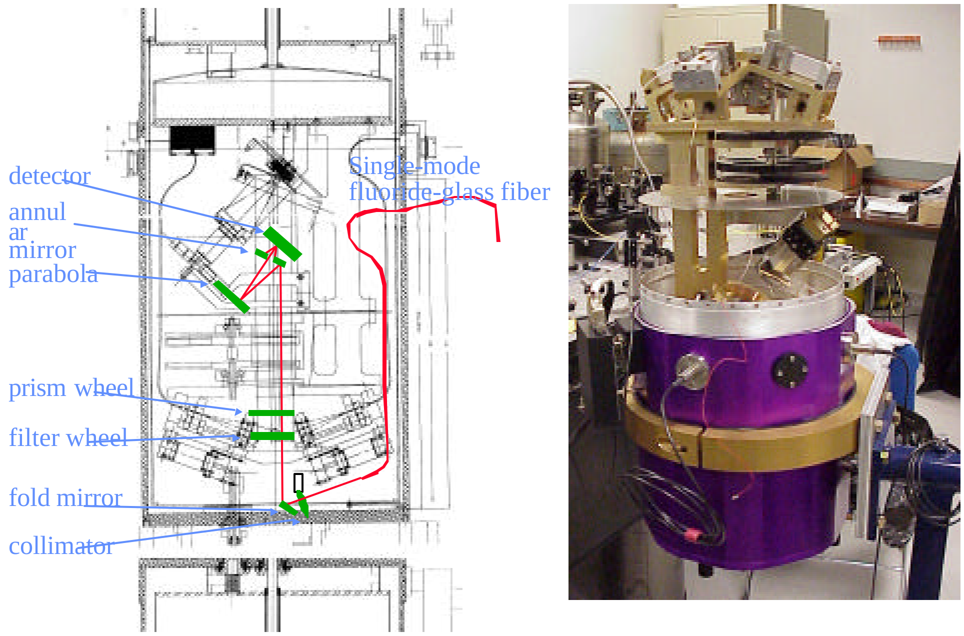

Figure 16: Fringe detector dewar schematic and photo during assembly (2/00).

Angle Tracker The angle tracker also uses a HAWAII infrared array in fast readout mode; the images from the six telescopes are arranged on a single quadrant. Angle tracking is provided at J and H. For the outriggers, this sensor is used for closing the loop with the fast tip/tilt secondary mirror on the telescopes. For the Kecks, where the AO system already provides high-speed angle tracking, the offsets from this angle sensor are used to correct for slow drifts. For application to cophased observation, including astrometry, a second angle tracker system will be implemented to providing slow guiding on the faint science stars.

Nulling Combiner As discussed above, the nulling combiner will be the primary instrument for the detection of exozodiacal dust disks, using an achromatic rotational shearing interferometer to null the light from the central star on two parallel 85-m baselines, which then feed a fringe-scanning beam combiner. The output of this combiner is spatially filtered and directed to a low-resolution 10 µm array camera. Both the nulling interferometer and the fringe-scanning beam combiner will be implemented in the cold box to minimize thermal emissivity. The nuller design draws heavily on work at JPL on the deep nulling of visible light.[7,8]

Imaging Combiner As imaging is the last mode to be implemented, the implementation of this six-way Michelson combiner is not yet finalized. Two options are under discussion: a non-redundant cross-dispersed design or a 6-way hybrid combiner.[19] The optical interface for both of these is the same (6 cophased collimated input beams).

7. Real-time control

The control of an instrument of this complexity is a major task; the following is just a high-level summary. Most of the real-time control is implemented using VME-based systems with Power-PC processors running VxWorks. The delay lines and starlight detector systems employ an object-oriented software framework (RICST[20]), running on top of VxWorks, that was developed at JPL for interferometry applications. Motion control and auto-alignment use EPICS,[21] which is a Keck standard, employed widely at the observatory for telescope and instrument interface. CORBA interfaces to RICST and EPICS subsystems allows uniform access by the interferometer sequencer for observing automation, by engineering and operator GUIs, and by the data archiver.

4. PROJECT STATUS

Major funding for the Keck Interferometer began in October 1997. As of the conference date, March 28, 2000, the siderostat site work is complete, the siderostats are installed, and the outrigger site work is in final design. The beam combining laboratory infrastructure is complete, and the delay line rails are installed and aligned. The first delay line, metrology, fringe and star tracker subsystems are in unit test at JPL. Laboratory subsystem integration is planned for the summer 2000, with mountain integration and test in the fall of 2000.

5. ACKNOWLEDGEMENTS

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