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The Keck Interferometer

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ABSTRACT

The Keck Interferometer is being developed by JPL and CARA as one of the ground-based components of NASA's Origins Program. The interferometer will combine the two 10-m Keck telescopes with four proposed 1.8-m outrigger telescopes located at the periphery of the Keck site on Mauna Kea. Incorporation of adaptive optics on the Keck telescopes with cophasing using an isoplanatic reference provides high sensitivity. Back-end instrumentation will include two-way combiners for cophasing and single-baseline measurements, a nulling combiner for high-dynamic range measurements, and a multi-way imaging combiner. Science objectives include the characterization of zodiacal dust around other stars, detection of warm stellar companions through multi-color differential-phase measurements, astrometric searches for Jupiter- and Uranus-mass stellar companions, and a wide range of infrared imaging.

Keywords: optical interferometry, astrometry, nulling, synthesis imaging, exozodiacal dust, extrasolar planets

1. INTRODUCTION

The Keck Interferometer will combine the two 10-m Keck telescopes with four proposed 1.8-m outrigger telescopes as an interferometric array capable of addressing a broad range of astronomical science. It is funded by NASA as a joint development between the Jet Propulsion Laboratory, California Institute of Technology (JPL) and the W. M. Keck Observatory, California Association for Research in Astronomy (CARA). The Keck Interferometer is a ground-based component of NASA's Origins Program.[1] Origins addresses fundamental questions about the formation of galaxies, stars, and planetary systems, the prevalence of planetary systems around other stars, and the formation of life on Earth.

The Keck Interferometer will use Michelson combination among the two Kecks and the four outriggers. The two Kecks provide a baseline of 85 m, while the baselines available with the outriggers will vary from 25 m to 140 m. The interferometer will combine phased pupils provided by adaptive optics on the Kecks and fast tip/tilt correction on the outriggers. Cophasing of the array will be accomplished by fringe tracking on an isoplanatic reference to enable high-sensitivity science observations. Key components of the cophasing system include active delay lines in the beam-combining lab and dual-star modules at each telescope. Several back-end beam combiners will be provided, including two-way beam combiners at 1.6–2.4 μm for fringe tracking, astrometry, and imaging; a multi-way combiner at 1.6–5 μm and 10 μm for imaging; and a nulling combiner for high dynamic range observations at 10 μm.

The design of the interferometer and its instrumentation is responsive to several key Origins science objectives. Science programs with the interferometer using the two Kecks include:

- Characterization of exozodiacal dust
  The quantity of exozodiacal dust around other solar systems is poorly known, especially down to levels near that of our solar system. The exozodiacal dust is a noise source for future space imaging missions like Terrestrial Planet Finder (TPF)[2], an infrared space interferometer designed to detect earth-like planets from their direct infrared emission. The Keck Interferometer will combine the two 10-m Keck telescopes using interferometric nulling to make this measurement down to levels less than ten times our solar system.
- Detection of super-Jupiters and brown dwarfs

Further information: http://huey.jpl.nasa.gov/keck.

Because of the different spectra of these objects compared with the stars they orbit, the center of light of the star-planet system is wavelength dependent and can be sensed with multi-wavelength phase measurements. Direct measurements allow detections in a single night for rapid confirmations of radial-velocity targets and for surveys of other candidate solar systems.

Science programs incorporating the outriggers with the Kecks include:

- Astrometric detection of exoplanets
  By sensing the reflex motion of a star caused by an orbiting planet, the Keck Interferometer will be able to survey hundreds of nearby stars for planets to Uranus mass.[3] The program uses the outriggers to implement high accuracy narrow-angle astrometry.
- Six-way interferometric imaging
  The interferometer can be configured for imaging using the 4 outriggers only, 4 outriggers with one Keck, and 4 outriggers with both Kecks. In the full 6-element mode, 9 of the 15 available baselines include at least one 10-m telescope; when background limited, the sensitivity of a 1.8-m/10-m pair is equivalent to two 4.4-m telescopes. The potential imaging science includes the observation of protoplanetary disks, to detect evidence of planetary formation, as well a variety of other Origins and astrophysical targets.[4]

Figure 1 shows the proposed layout of the interferometer at the Keck site on Mauna Kea, Hawaii. Below, we briefly describe the interferometer components, and then return to describe the implementation of the science observations listed above.

2. INTERFEROMETER SUBSYSTEMS

The Keck Interferometer integrates a number of different subsystems; these are described very briefly below. The intent of the design is to provide modularity to allow concurrent development and simplified integration, and to provide a clean interface for the back-end instruments.

2.1. Telescopes

The apertures for the interferometer include the two existing 10-m Keck telescopes, as well as four proposed 1.8-m outrigger telescopes. The outriggers are used for the astrometric program, and with the Kecks for synthesis imaging. Because of their use for astrometry, the outriggers have tight specifications on their pivots in order to allow high accuracy measurements. For interferometer debugging, two 40-cm siderostats with fixed compressor telescopes will be installed to debug the interferometer systems prior to integration with the Kecks or the outriggers. These siderostats will be similar to those used by the Palomar Testbed Interferometer (PTI),[5] which serves as a testbed for a number of aspects of the Keck Interferometer.

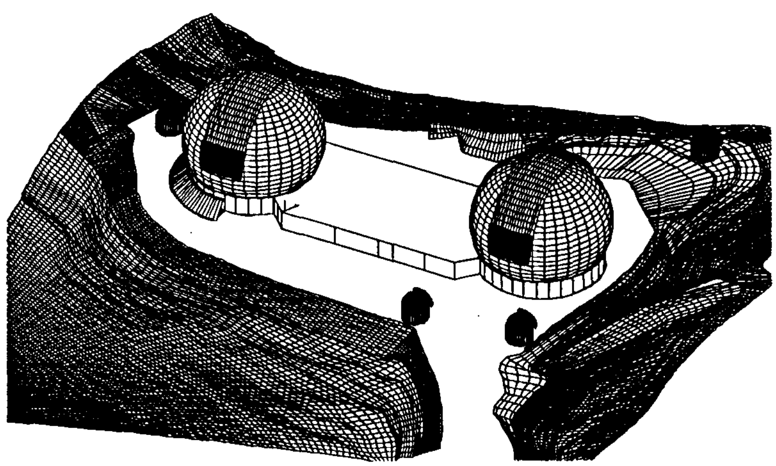


Figure 1

2.2. Wavefront correction

The Keck Observatory is currently developing an adaptive optics system for Keck-2[6]. As part of the interferometer project, a second adaptive optics system will be developed for Keck-1, providing phased pupils at near- and mid-IR wavelengths. For the smaller outrigger telescopes, fast tip/tilt compensation will be implemented using an active secondary and a 1.2-μm wavefront sensor at the interferometer back end. For 1.8-m telescopes at Mauna Kea, tip/tilt compensation is adequate for observations at 1.6 μm and longer wavelengths.

2.3. Dual-star module

To enable cophasing using an isoplanatic reference, a dual-star module is installed at each telescope. The dual-star module selects two objects in the telescope field of view, and collimates and directs the light into the interferometer beam train. One of these objects will be bright (primary star) and serve as the phase reference for the other object (secondary star). On the Kecks, the dual-star module will slide in adjacent to the adaptive optics bench, similar to NIRSPEC.

2.4. Coude train and beam transport

To propagate the light from the dual-star module on the Nasmyth deck of each Keck telescope, the Keck coude train will be completed with the addition of coude mirrors M4–M7 (M4 is the output mirror of the dual-star module, while M7 is the fixed mirror at the base of the telescope). As two beams are propagated from the dual-star feed, each coude mirror is

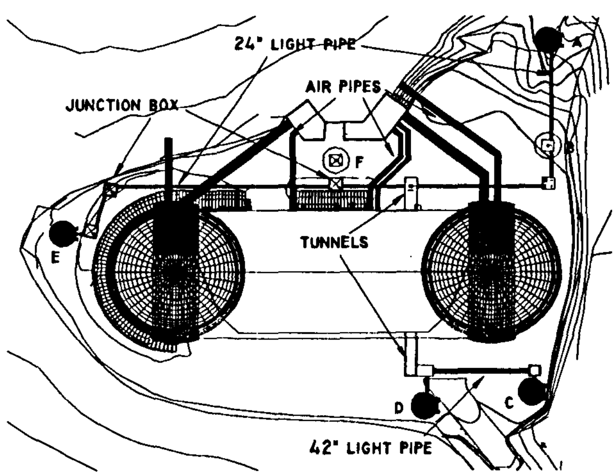


Figure 2

actually a mirror pair. For the primary star, these mirrors are located along the coude centerline; for the secondary star, these mirrors are offset from the centerline and are actuated to compensate for azimuth rotation. A similar coude system is needed for the outrigger telescopes. After mirror M7, the light is directed into the beam-combining lab located in the basement of the Keck facility. For the outriggers, the light is directed using buried pipes, as illustrated in Figure 2; for the Kecks, the light from the M7 mirrors is directed into the coude tubes which pass through the telescope footings into the coude tunnel which connects the two telescopes.

2.5. Delay lines

The delay lines on the interferometer will be implemented in two stages. The *long delay lines* will be located in the coude tunnel between the two Kecks. They use adjustable range mirrors that move along tracks in the tunnel. The range mirrors are flat, and delay both the primary and secondary beam identically. The are repositioned only between stars, and remain fixed during an observation. The *fast delay lines* are located in the beam-combining lab, shown schematically in Figure 3. There are separate fast delay lines for the primary and secondary beams from each telescope. These delay lines move continually during the observation to track sidereal motion and atmospheric turbulence; separate delay lines for the two stars enables phase referencing with feedforward, and different pathlength modulations for fringe demodulation. The fast delay lines will be similar to those used at PTI; a 20-m delay range per delay line will allow significant sky coverage without repositioning the long delay lines.

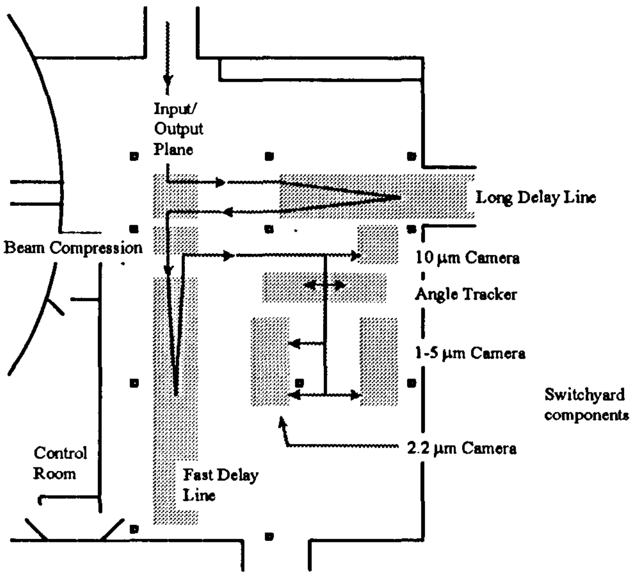


Figure 3

2.6. Pathlength sensing

Pathlength sensing on the interferometer includes:

- Local metrology of the fast delay lines. This is implemented with a conventional heterodyne metrology system, and will be used primarily for delay-line servo control.
- End-to-end, or constant-term, metrology of the complete optical path from beam combiner to dual-star module. This metrology references the primary and secondary beam paths to identical fiducials in order to implement cophasing and narrow-angle astrometry. The metrology will also monitor vibrations in the beam-transport optics.
- Accelerometer sensing of coude optics. Accelerometers on key optics not in the optical path will be used to monitor vibrations which could affect fringe visibility. Vibrations measured with the accelerometers will be fed forward to the delay lines for high-bandwidth compensation.

2.7. Angle tracker

Angle tracking will be implemented at 1.2 µm using an infrared array in a fast-readout mode. For the primary beams from the Kecks, the angle tracker will provide low-bandwidth track offsets to the adaptive-optics systems. For the primary beams from the outriggers, centroids determined from the angle sensor will control active secondary mirrors on the telescopes. For the secondary beams from both telescopes, the angle tracker will provide low-bandwidth track offsets to the dual-star modules.

2.8. Fringe tracker

The fringe tracker will provide five identical two-way beam combiners; each of these will be very similar to those in use at PTI. The detectors will be a HgCdTe infrared arrays used in fast-readout mode, sensing at 1.6–2.4 µm. The detectors for all of the combiners will be remotely located in two fiber-fed dewars, fed via post-combination single-mode IR fibers. The fringe trackers support all of the observing modes of the interferometer. For cophasing, fringes are tracked on up to 5 baselines to cophase the 6 telescopes. For astrometry, two of the beam combiners will track the bright primary star on orthogonal baselines, while two others will track the faint secondary star.

2.9. Multi-way combiner

The multi-way combiner will provide pair-wise fringe measurements on up to 15 baselines simultaneously. The proposed configuration is a non-redundant cross-dispersed design, which provides unique spatial frequencies along one dimension of the infrared array to code baselines, with frequency information provided along the other dimension. The detectors would include a 5-µm–cutoff HgCdTe array and a 10-µm Si:As BIB.

2.10. Nulling combiner

The nulling combiner will implement two stages of achromatic nulling interferometers feeding a Si:As BIB detector. Nulling is discussed in more detail in Section 0.

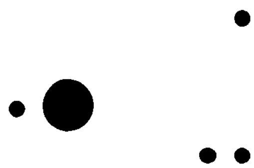
2.11. Other subsystems

An optical switchyard will provide automated reconfiguration among the various observing modes. A stimulus will provide white-light and laser sources for boresighting, calibration, and testing. An automated alignment system will provide low-bandwidth sensing of alignment beacons at the periphery of the beam-transport optics and long delay lines to control the mirror tilts.

3. OBSERVATIONAL MODES

The observational modes of the interferometer are illustrated in Table 1; the key science modes are discussed below.

Table 1

Configuration	Use	Science	Plan view
Siderostats only	Interferometer subsystem testing	Testing only	
Two Keck Interferometer	Initial operation as Interferometer	Exo-zodiacal emission, Hot-Jupiters	
Single Keck + Outriggers	High resolution and high sensitivity imaging mode	General imaging: YSOs	
Complete Imaging Array	Highest resolution imaging, highest sensitivity	General imaging: Planetary formation	
Outriggers alone	Astrometry, Imaging	Astrometric planet detection, General imaging	

3.1. Characterization of exozodiacal dust

The key scales of the detection problem are illustrated in Figure 4 for a source at 10 pc. For a typical G star, its apparent diameter would be about 1 mas. The figure illustrates a 1-AU–radius zodiacal dust cloud around the star which subtends a full angle at 10 pc of 200 mas. The detection problem has two parts. For an exozodiacal dust cloud with a density equal to 10 times our solar system, the intensity ratio between the star and the integrated exozodiacal signal is 1000:1. Furthermore, at 10 μm, which is the preferred wavelength for this observation, both of these signals are deeply embedded in the 10-μm thermal background. Nevertheless, with the high sensitivity provided by the 10-m apertures of the Kecks, the photometric signal-to-noise ratio is high, allowing in principle 1-σ detections of exozodiacal dust clouds as faint as one solar-system equivalent.

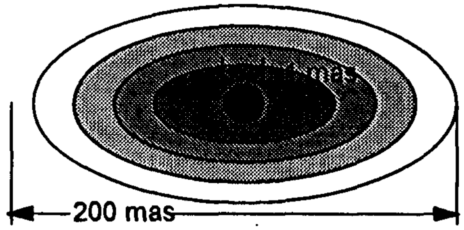


Figure 4

The key to the measurement technique proposed for the Keck Interferometer is to use interferometric nulling to distinguish the exozodiacal signal from the star, and to provide an ac signal for synchronous detection. Figure 5a illustrates the technique. An achromatic rotational shearing nulling interferometer is implemented for each aperture separately, followed by an achromatic nulling interferometer that combines the outputs of the two aperture nullers. The achromatic nullers use polarization rotation, rather than a phase shift, in order to provide a null with matched internal optical paths[7]. Thus the two stages provide nulling on two different spatial scales: the aperture nullers provides nulls at a characteristic scale of 200 mas at 10 μm, corresponding to the aperture diffraction limit, while the interferometer nuller provides a null at a characteristic scale of 25 mas, corresponding to the 85-m separation between the two Kecks. The transmission of an exozodiacal cloud though each of these nulls is illustrated in Figure 5b: while the interferometer null primarily attenuates the star, the aperture null attenuates both the star and the exozodiacal dust cloud. These nulls can be modulated on and off by changing internal optical paths in order to implement source chopping while remaining pointed at the source. By modulating both the aperture and interferometer nullers, ac signals are provided to allow separate detection of the exozodiacal dust and the star in the presence of the thermal background.

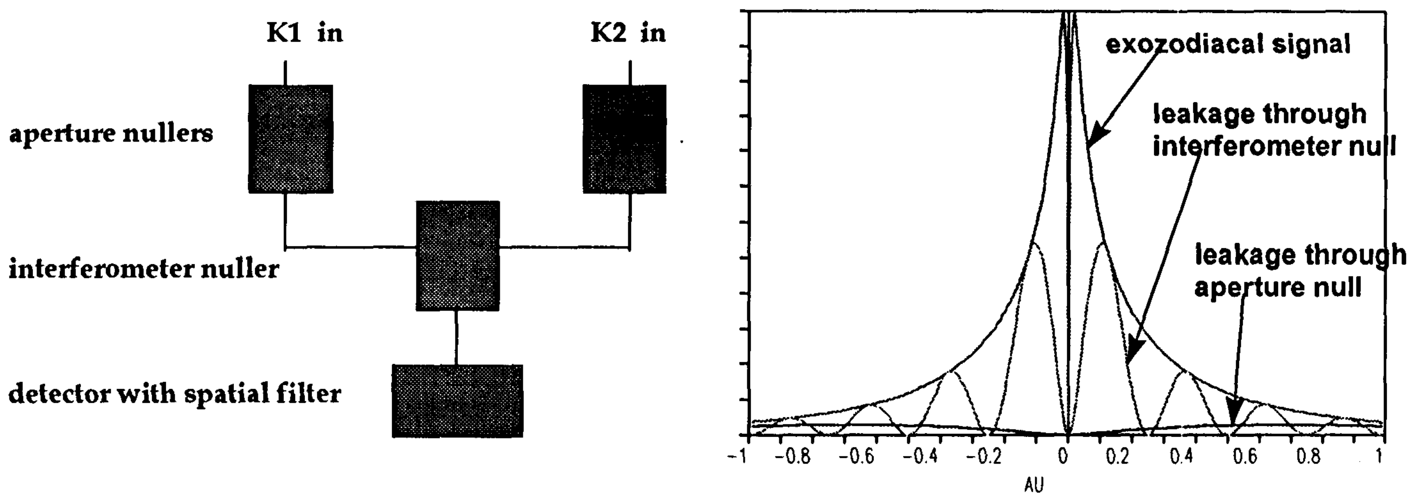


Figure 5

(a) **(b)**

3.2. Detection of super-Jupiters and brown dwarfs

Recent observations have detected a number of "super-Jupiters" from measurements of the radial velocities of their parent stars. While they are faint in comparison to their parent stars, it should be possible to detect these objects from their direct infrared emission. The principle of the observation is illustrated in Figure 6; it exploits the temperature difference between the planet and the parent star. At short wavelengths, as illustrated in the upper panel, the intensity ratio between the star and the planet is quite large. Thus the fringe position of the system—essentially the center of light—will lie very close to the star. However at longer wavelengths the intensity ratio between the star and the planet, while still large, is more favorable to the planet, and the center of light will be displaced toward the planet. Thus, simultaneous measurements of a planetary system at two different wavelengths can be used to detect the planet; rotational synthesis can be used to determine a planetary orbit.

As the center of light shift is quite small, and must be detected in the presence of atmospheric turbulence, the multi-wavelength measurements must be made simultaneously with a single beam combiner. For some objects, especially the brown dwarfs, which may have significant structure in their near-IR spectra, detection could use the 1.6–2.4 μm coverage of the fringe-tracking detectors. For other objects, the detector of choice would be the 1.6–5.0 μm multi-way combiner. The large apertures of the Kecks provide high sensitivity. For example, for a 1300 K planet around a G star at 10 pc, and simultaneous observations at 2.2 μm and 5.0 μm, a signal-to-noise ratio >10 is achieved in one second of integration. The primary systematic that must be calibrated is atmospheric dispersion, which will require observation of nearby calibrators.

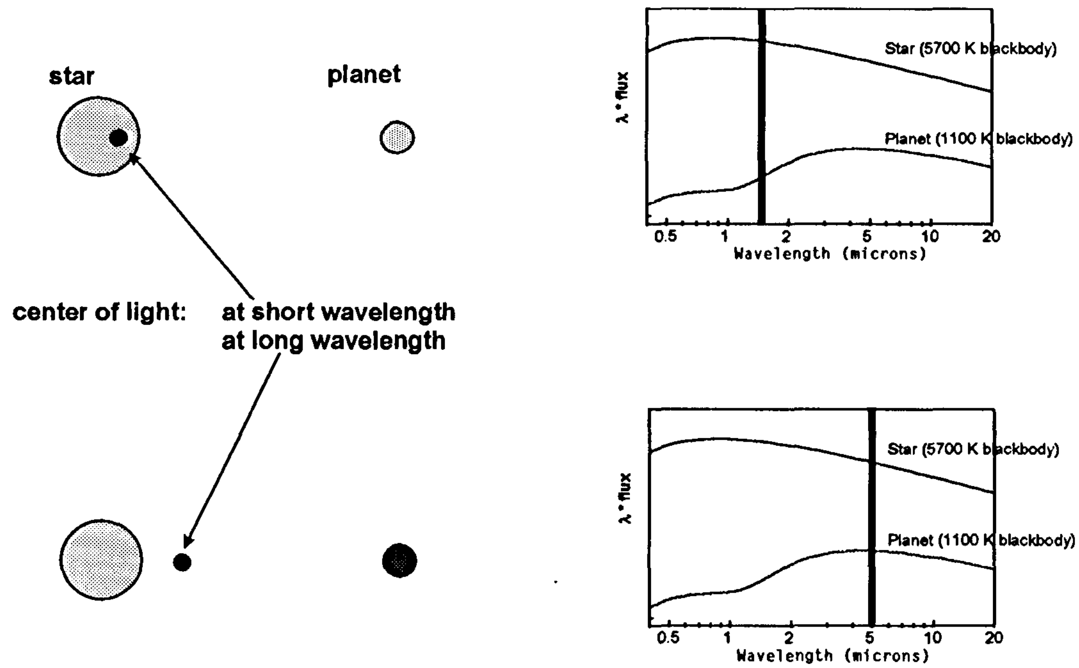


Figure 6

3.3. Astrometric detection of exoplanets

For the astrometric detection of exoplanets, the interferometer is configured using the four outrigger telescopes to provide two approximately orthogonal baselines, each >100 m long. For each baseline, a phase-referenced measurement is made between a star which may have a planetary companion, and one or more faint astrometric references within a 20–30-arcsec radius of the first star. For stars in the nearby sample, for which the astrometric technique is most sensitive, the target star serves as the cophasing source (primary star), allowing high sensitivity to detect the astrometric references (secondary stars).[8] The error budget for this observation includes terms attributable to atmospheric turbulence, photon noise from the reference stars, and residual baseline and constant-term metrology errors. The objective is an accuracy of 20 μas in a one-hour differential measurement. More detail on astrometry with the Keck Interferometer is presented in Ref. 3.

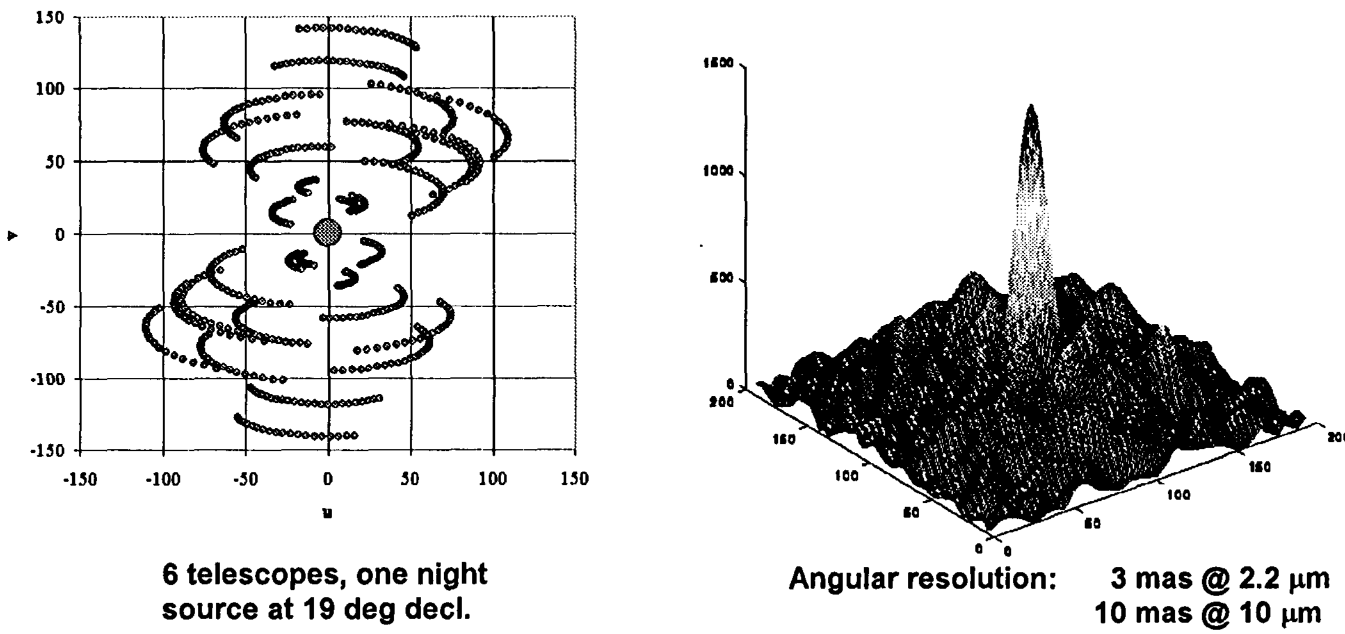


Figure 7

(a) (b)

3.4. Six-way interferometric imaging

Combining the light from the two Kecks with the four outriggers provides 15 simultaneous baselines. Cophasing would be implemented in the near-IR using an isoplanatic reference from the dual-star feed. Cophasing would be implemented on five baselines: from each outrigger to a Keck, and from Keck to Keck. This division of light takes advantage of the large Keck apertures: while the cophasing light from each Keck is split 3 ways, there is no splitting required on the outriggers. When cophased, coherence-time limitations on the science object are removed, and high sensitivity is possible. Figure 7a shows the (u,v) coverage provided by the six telescopes, while Figure 7b shows the point-spread function. Table 2 presents the predicted sensitivity for the interferometer at different wavelengths. More detail on imaging with the Keck Interferometer is presented in Ref. 4

Table 2

On-axis Full Array Cophasing Limit:	4 Outriggers	1 Keck + 4 Outriggers		2 Kecks + 4 Outriggers		
	2m / 2m	*10m / 2m*	*2m / 2m*	*10m / 10m*	*10m / 2m*	*2m / 2m*
2.2 um	11.0	12.8	N/A	15.0	12.9	N/A

Off-axis Limit:	Astrometric	4 Outriggers	1 Keck + 4 Outriggers		2 Kecks + 4 Outriggers		
	2m / 2m	*2m / 2m*	*10m / 2m*	*2m / 2m*	*10m / 10m*	*10m / 2m*	*2m / 2m*
1.6 um	N/A	19.1	21.2	19.0	23.5	21.0	18.8
2.2 um	17.0	18.2	20.1	18.0	22.1	20.0	17.9
3.5 um	N/A	13.5	15.3	13.3	17.1	15.1	13.2
5 um	N/A	11.0	12.7	10.8	14.5	12.6	10.7
10 um	N/A	7.5	9.2	7.3	10.9	9.1	7.2

SNR=10 for cophasing, K only
SNR=10 per baseline in 1000 sec for imaging
SNR=72 in 3600 sec for astrometry

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