Optical engineering for high angular resolution at Keck observatory

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The role of optical engineering in providing large apertures and high resolution is illustrated by two interferometer-linked telescopes at W. M. Keck Observatory.

Bigger is better in the field of astronomical telescopes. Larger primary mirrors offer more collecting area, allowing astronomers to detect fainter and more distant objects. Angular resolution also grows with primary mirror size—provided the blurring due to turbulence in the earth's atmosphere can be corrected—as, therefore, does the telescope's ability to resolve the structure of astronomical objects.

Until the early 1990s, the largest optical telescopes in the world were the Palomar 5m and Russian 6m telescopes. A new generation of 4m-class telescopes built in the 1960s and 1970s introduced considerable technological advancements without challenging these existing giants for collecting aperture. Then, a dramatic change occurred in the 1990s with the commissioning of the 10m Keck I and Keck II telescopes for science (see Figure 1). The new science capability that resulted has had a huge impact on our understanding of the universe. This Keck first was followed in the past decade with the commissioning of multiple 8m-class telescopes that use a segmentation approach to produce a large primary mirror. Most other large telescopes have monolithic primary mirrors, using either thin-meniscus or honeycomb structures so that they are light in weight. The community is now funding design studies for 20m- to 100m-class telescopes.

The Keck telescope primary mirrors each consist of 36 hexagonal elements made from a glass ceramic material called Zerodur. Each segment is part of an off-axis hyperbola with a focal ratio of f/1.75: the techniques of stress-mirror polishing and ion figuring were developed to achieve the desired optical surface. Each segment (see Figure 2) is mounted on a 36-point whiffletree structure and a radial post, with their position controlled in tip/tilt and piston by three actuators. The relative piston of neighboring segments is sensed by capacitive sensors between them. Three secondary mirrors are available to produce focal ratios of f/15, 25 and 40. A tertiary mirror can fold the beam to the Nasmyth and bent-Cassegrain foci.

A multi-mode Shack-Hartmann camera is used to provide the information to align the segments and secondary mirror in tip, tilt, and piston and to correct the individual segment aberrations using warping harnesses incorporated in the segment whiffletrees. The relative piston is determined from the interference within apertures that overlap the edges of each pair of adjacent segments. Once the primary mirror has been stacked and phased, an active control system maintains the phasing as the telescope moves in elevation. The resultant median image FWHM (full width at half maximum) from routine monitoring is 0.58 arcseconds (over a recent six-month period) with best images of 0.30 arcseconds.

Figure 1. W. M. Keck Observatory atop Mauna Kea, Hawaii. (Photo credit: R. Wainscoat.)
Another dramatic success of the 1990s was the first implementation of adaptive optical (AO) systems on astronomical telescopes. Due to the blurring effect of turbulence in the earth’s atmosphere, large telescopes offer no improvement in angular resolution over small telescopes (though they do, of course, offer a significant increase in collecting area). AO corrects for this blurring by using the light from a natural guide star (NGS) to sense the wavefront distortion and a deformable mirror to correct for this distortion. The need for a relatively bright NGS has limited AO science to a small fraction of the sky. This limitation is being lifted with the use of artificial laser guide star (LGS) systems (see Figure 3). The Keck telescopes were the first of the generation of 8 to 10m telescopes to be equipped with both NGS and LGS AO.1–3

The AO systems are mounted on the Nasmyth platforms of the Keck telescopes (see Figure 4). On Keck II, four near-infrared science instruments are available: a near-infrared camera (NIRC2), a near-infrared spectrograph (NIRSPEC), an integral field spectrograph (OSIRIS), and a dual-star module (DSM) that feeds light to the interferometer located in the basement between the two Keck telescopes.

A number of new AO projects are underway at Keck including implementation of next-generation real-time wavefront controllers and sensors, the implementation of a solid-state laser system on Keck I and the conceptual design of a higher performance LGS AO system capable of providing AO correction down to visible wavelengths.

Another approach to increasing angular resolution is to interferometrically combine the light from two or more telescopes. In the field of large telescopes, this is being done with the twin Keck telescopes4,5 and the four 8m telescopes of the European Southern Observatory. The 85m Keck baseline provides an angular resolution of 5 milliarcseconds at a 2μm wavelength. The AO-corrected light from each telescope is relayed through a series of mirrors to the basement between the two, where the optical paths are matched before the light is interfered. The available science mode consists of fringe-visibility measurements on a near-IR camera. The contrast of the interference fringes is used to determine the size, or other characteristics, of the object being studied.

A key science goal for the Keck Interferometer, as part of NASA’s Origins program, is to measure the dust around other solar systems in support of future space missions. This is accomplished by nulling the 10μm-wavelength light. The nuller first interferes the left halves of the two telescopes, and separately the right halves, to null out the light from the star. The nulled left and right halves are then interfered to measure the level of exo-zodiacal dust.

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A longer-term step could be to combine up to seven AO-equipped telescopes on Mauna Kea with optical fibers to produce an 800m interferometer. Fiber combination between the two telescopes was recently demonstrated as one step in this development program.6

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**References**


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**Figure 4.** Left: The AO enclosure on the Nasmyth platform of the Keck II telescope. Right: A schematic view of the AO enclosure with its roof removed (for scale, NIRC2 is 1.5m in length).