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W. M. Keck Observatory

Instrumentation, Adaptive Optics, and Scientific Productivity

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Abstract

For the past fifteen years, the W. M. Keck Observatory has played a leading role in astronomy and astrophysics. This paper discusses the instrumentation and adaptive optics systems at Keck Observatory with an emphasis on recent developments and future plans. It also discusses the high scientific productivity of Keck Observatory using various metrics. Keck Observatory's strategy to remain highly scientifically productive is outlined, with an emphasis on how the strategy is influenced by the design and construction of new facilities, particularly extremely large telescopes.

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1. Overview of W. M. Keck Observatory

The W. M. Keck Observatory (WMKO) operates twin 10 meter optical/infrared telescopes on the excellent site of Mauna Kea. Keck I achieved first light in 1992 and Keck II in 1996. The two telescopes feature a highly capable suite of advanced instrumentation for both optical and near-infrared wavelengths, including imagers, multi-object spectrographs, high-resolution spectrographs, and integral-field spectroscopy. WMKO has developed and operates a sophisticated natural and laser guide star adaptive optics system and related instrumentation. The Observatory also operates the only large-aperture infrared interferometer in the U.S., and one of only two such interferometers in the world.

The partners in the operation of Keck Observatory are Caltech, the University of California and NASA. The University of Hawaii participates in Keck observing by providing access to Mauna Kea. The allocation of observing time is divided among these institutions as follows: Caltech (36.5%), University of California (36.5%), NASA (14.5%), and University of Hawaii (12.5%). Yale University and the Swinburne Institute of Technology participate in Keck observing via a partnership with Caltech. The broad U.S. community gains peer-reviewed access to the Keck telescopes via the NASA partnership and through the NSF/NOAO Telescope System Instrumentation Program (approximately 24 nights per year).

2. Current Keck Instrumentation

Keck Observatory offers a wide range of highly capable instrumentation. Table 1 lists all of the observing capabilities offered at Keck Observatory. Instrumentation that works in conjunction with the Keck adaptive optics is covered in Section 3. WMKO's suite of efficient, state-of-the-art instruments has been a key factor in its success.

Optical spectroscopy at low to moderate spectral resolution is provided by LRIS, DEIMOS and ESI. LRIS is a dual-beam multi-object spectrograph and imager first commissioned in 1994. It later received CCDs with high sensitivity for its blue channel, and LRIS's excellent blue sensitivity is one of its strengths. DEIMOS provides R = 6,000 multi-object spectroscopy over a field of 16.3 arcmin × 5 arcmin. DEIMOS became fully operational in 2002. ESI is a high-throughput, echellette spectrograph that was commissioned in 1999.

High-resolution optical spectroscopy is provided by HIRES, a large echelle spectrograph with a resolving power of 30,000 to 80,000. It includes an optional iodine cell for precision radial velocity calibrations and is housed in a thermally stable environment. HIRES has been very productive in exoplanet detection and charac-

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terization using the Doppler wobble technique. Originally commissioned in 1994, HIRES's CCD camera and electronics were upgraded in 2004 for greater sensitivity and wavelength coverage.

NIRSPEC is a cross-dispersed cryogenic echelle spectrograph with wavelength coverage from 0.95 to 5.5 microns. NIRSPEC has two modes: low-resolution spectroscopy with R = 2,000; and high-resolution, cross-dispersed spectroscopy with R = 25,000. NIRSPEC is relatively unique in providing high-resolution, cross-dispersed infrared spectroscopy on a large telescope.

Telescope	*Instrument*	*Initials*	*Bandpass*	*Field of View*	*Resolving Power*
Keck I				82 sq. arcmin	
	High Resolution Echelle Spectrometer (blue cross disperser)	HIRESb	0.31-0.65 microns	(0.4", 0.574", 0.861", 1.148", 1.722") X (3.5", 7", 14", 28") slits	24,000-84,000
	High Resolution Echelle Spectrometer (red cross disperser)	HIRESr	0.42-1.0 microns	(0.4", 0.574", 0.861", 1.148", 1.722") X (3.5", 7", 14", 28") slits	25,000-87,000
	Low-Resolution Imaging Spectrometer	LRIS	0.3-1.1 microns	6×7.8 arcmin	400-3600
	LRIS polarimeter	LRISp	0.3-1.1 microns	20x20 arcsec	400-3600
	MOSFIRE (arriving in 2010)	MOSFIRE	1.0-2.4 microns	6.1x6.1 arcmin	3270
Keck II					
	Deep Imaging Multi-Object Spectrometer	DEIMOS	0.4-1.1 microns	94 sq arcmin	1,000-6,000
	Echellette Spectrometer and Imager	ESI	0.39-1.1 microns	16 sq arcmin	1,000-13,000
	Near-IR Spectrometer (low dispersion)	NIRSPEC-L	0.95-5.4 microns	0.7 x 42 arcsec	2000
	Near-IR Spectrometer (high dispersion)	NIRSPEC-H	0.95-5.4 microns	0.7 x 12 arcsec	25,000
	Near-IR Spectrometer (behind AO)	NIRSPAO	0.95-2.6 microns	0.04 x 2.24 arcsec	25,000
	Near-IR Camera 2 (imaging)	NIRC2	1.0-5.0 microns	10 x 10, 20 x 20, and 40 x 40 arcsec	
	Near-IR Camera 2 (spectroscopy)	NIRC2	1.0-5.0 microns	(0.010-0.160 arcsec) x (10-40 arsec)	1000-5000
	OH Supressing IR Integral-field Spectrometer	OSIRIS	1.0-2.4 microns	4.8 x 6.4 arcsec	3800
Keck	Keck Interferometer				
Interferometer	Nulling mode	Nuller	N	251 milliarcsec	
(Keck I + II)	Standard visibility-squared (V2) mode	V2-H	H	41 milliarcsec	
	Standard visibility-squared (V2) mode	V2-K	K	55 milliarcsec	
	Standard visibility-squared (V2) mode	V2-L	L	91 milliarcsec	
	High dispersion V2 mode	V2-SPR	K	55 milliarcsec	1800
	High sensitivity V2 mode	V2-DFPR	K	55 milliarcsec	
	Astrometry mode	Astrometry	K	30 arcsec	

Table 1: Keck Observing Capabilities

During 2009, the red arm of LRIS was upgraded. A new red camera for LRIS replaces the existing CCD in the red side of LRIS with a 2 × 1 mosaic of 2048 × 4096 high-resistivity thick substrate LBNL CCDs. These CCDs were acquired and deployed in order to substantially enhance the red sensitivity compared to the former CCD. In addition, due to their thick substrate, these CCDs exhibit no fringing. Observers are also benefitting from a modest increase in spatial and spectral coverage, more uniform image quality due to a flatter detector, and increased reliability from the new CCD control electronics.

3. Keck Adaptive Optics

With primary mirror diameters of 10 meters, the Keck telescopes are among the largest ground-based telescopes and therefore have the potential to obtain the highest spatial resolution of any telescope once the effects of atmospheric turbulence are mitigated. Thus, Keck Observatory has a long-standing and ambitious adaptive optics program. The existing adaptive optics systems on Keck II and Keck I were commissioned in 1999 and 2000 respectively. Initially, both systems carried out natural guide star adaptive optics observations, and Keck was the first of the large telescopes with a natural guide star system. The Keck II system was designed to accomplish laser guide star observations

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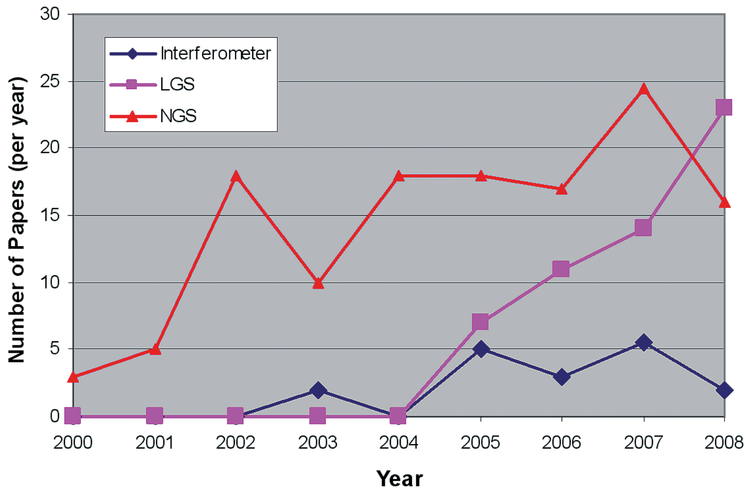
as well, and a laser was added and the system commissioned in 2003-2004 (Wizinowich et al. 2006). Keck was the first large telescope to deploy laser guide star adaptive optics. Laser guide star adaptive optics overcomes the restriction of requiring a bright natural guide star close to the object being studied, and thus enables adaptive optics observations over most regions of sky. Under typical atmospheric conditions, the laser guide star system yields K-band Strehl ratios between 30% and 40% (using bright tip-tilt stars).

The two primary instruments used with the Keck II adaptive optics system are NIRC2 and OSIRIS. NIRC2 is a near-infrared instrument optimized to exploit the images provided by Keck II's adaptive optics system. NIRC2's camera has three pixel scales and provides coverage from 1 to 5 microns. NIRC2 also provides grism spectroscopy at low and moderate spectral resolution. NIRC2 achieved first light in 2001. OSIRIS is an OH-suppression infrared integral field spectrograph that achieved first light in 2005. OSIRIS employs a focal plane lenslet array to enable diffraction-limited R=3,900 integral field spectroscopy with the adaptive optics system. OSIRIS provides four pixel scales from 0.02 arcsec to 0.1 arcsec.

The Keck adaptive optics systems have been a great success and have been applied to a wide variety of astronomical targets and investigations. As shown in Figure 1, the scientific productivity of adaptive optics at Keck has been high. Papers based on natural guide star and laser guide star adaptive optics are shown separately in Figure 1. The production of papers from the more recent laser guide star system has increased significantly since installation, and in 2008 papers from the laser guide star system surpassed for the first time those resulting from natural guide star observations.

Figure 1: The number of refereed Keck papers published each year based on adaptive optics is plotted against year of publication. Papers based on natural guide star observations (NGS), laser guide star observations (LGS), and Keck-Keck interferometry are shown separately. Note the rapid rise in the number of LGS papers in recent years.



An upgrade to the wavefront sensors and wavefront controllers of the Keck I and II adaptive optics

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systems was successfully carried out and commissioned in 2007 (Johansson et al. 2008). By replacing aging components in these systems with new technology, significant gains were achieved in limiting guide star magnitude and Strehl ratio for both natural guide star and laser guide star modes. Reliability and maintainability were also enhanced.

4. Future Enhancements to Instrumentation and Adaptive Optics

MOSFIRE is a near-infrared multi-object imaging spectrograph for the Cassegrain focus of Keck I. This instrument will provide a field of view of 6.8 arcmin in diameter for imaging, and it will enable spectroscopy at R = 3,000 for 46 slits over a field of view of 6.1 arcmin × 3 arcmin. MOSFIRE will deliver almost full band spectral coverage in Y, J, H, or K. The multi-slit capability is delivered by an innovative cryogenic configurable slit unit that operates under computer control. Unlike most other near-infrared multi-object spectrographs, thermal cycling of the instrument is not required to reconfigure the multi-slits. MOSFIRE is being developed and fabricated for Keck Observatory by a consortium consisting of Caltech, UCLA, and the University of California Observatories. As of July 2009, MOSFIRE is in the integration and test phase, undergoing cold cycles. Delivery and commissioning is expected in 2010.

An upgrade of the Keck I adaptive optics system to a laser guide star system is currently underway. This project, which will deploy a new solid-state laser from Lockheed Martin Coherent Technologies and a center-laser-launch telescope, will deliver improved performance relative to the Keck II system. In addition, it will provide redundancy against failure of the Keck II adaptive optics system and will enable using laser-guide-star adaptive optics to extend the performance of the Keck Interferometer. Once the Keck I laser guide star adaptive optics system is complete and commissioned, expected for 2010, the OSIRIS integral field spectrograph will be moved from Keck II to Keck I to take advantage of the system.

In order to further exploit the benefits of adaptive optics observations and to respond to enthusiasm from our observer community for even greater adaptive optics performance than delivered by existing systems, Keck Observatory has embarked on the design and development of a Next Generation Adaptive Optics System (NGAO; Wizinowich et al. 2008; Max et al. 2008). NGAO has five goals: 1) provide diffraction-limited performance in near-infrared (K-band Strehl ratio > 80%); 2) provide good AO correction at red wavelengths (0.7-1.0 microns); 3) deliver increased sky coverage; 4) enable improved angular resolution, sensitivity and contrast relative to the current Keck II adaptive optics system; 5) provide improved photometric and astrometric accuracy. New optimized instrumentation for imaging and integral field spectroscopy will be developed with NGAO. In order to achieve the above goals, the system features multiple sodium laser guide star tomographic wavefront sensing

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to overcome the cone effect. A cooled AO system would be implemented to meet the infrared background requirements.

NGAO successfully passed its system design review in April 2008 and is currently in the preliminary design phase. NGAO should enable a wide variety of new and impactful science through improved sensitivity, higher Strehls, improved PSF knowledge and stability, increased sky coverage, and performance at shorter wavelength.

NGAO will offer a set of observing capabilities that are not available at any other observatory. Almost all other second-generation adaptive-optics development projects are targeting either wider-field seeing improvement (e.g., ground layer adaptive optics) or very high contrast adaptive optics with the goal of detecting extrasolar planets. The one exception is the Gemini South MCAO system, which is a multiple laser system that employs tomography like NGAO. However, MCAO's objective is more modest Strehl ratios over a wider field compared to NGAO. NGAO is unique among current large telescope adaptive optics development projects in seeking to deliver diffraction-limited images in the infrared and significant high-order correction at red wavelengths.

5. Keck Observatory Scientific Productivity

Although there are now a significant number of 6-10 meter optical/infrared ground-based telescopes, by almost all measures, Keck Observatory has maintained the lead in research productivity. Figure 2 shows the number of refereed publications per year based on data obtained using the WMKO from 1996 to present. The number of refereed publications per year has increased with time. This increase in productivity can be attributed to the frontier instruments and adaptive optics systems that have been installed on the Keck telescopes over the period between first light and today. The modest drop of papers in 2008 compared to 2007 is likely attributable to the publication of many papers from the DEEP2 survey in 2007 and the fact that several weeks of observing time were lost in late 2006 due to a major earthquake and the need for repairs afterward (there is, of course, a lag between the acquisition of astronomical data and its publication).

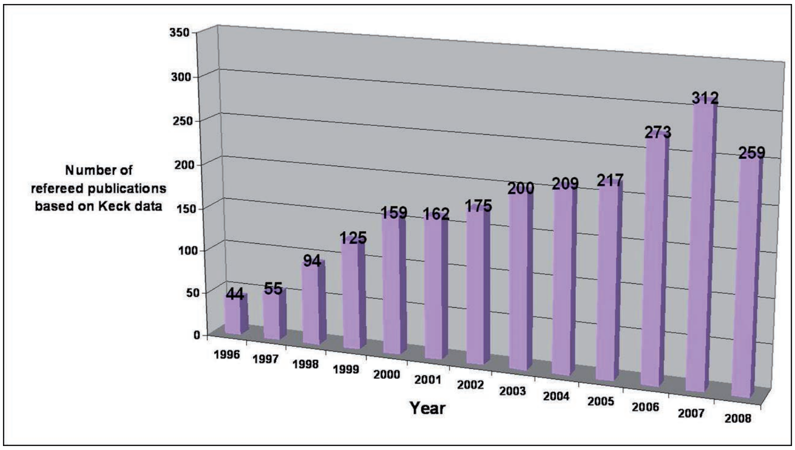

Figure 2: Number of refereed publications per year based on data from W. M. Keck Observatory.

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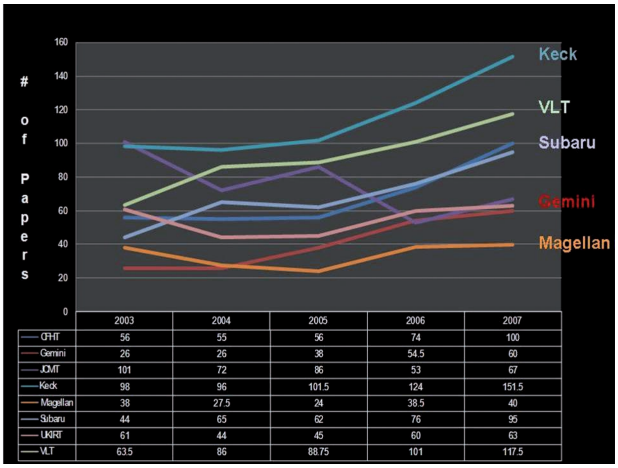
Keck currently produces approximately 150 papers per telescope per year, which as shown in Figure 3, exceeds the scientific output of any other ground-based observatory in the world.

The impact of papers based on Keck Observatory data also significantly exceeds that of peer observatories. Crabtree (2008) showed that Keck Observatory has the most highly and extremely cited papers and the fewest weakly cited papers compared to all other major optical/infrared telescopes (both ground and space-based). The comparator group in this study includes the ESO VLT, Gemini, Subaru and Hubble Space Telescope. A study conducted by ESO staff (Grothkopf et al. 2007) compares the scientific impact of four major observatories with 8-10 meter telescopes based on the h-index, where the counted publication number equals the number of citations, in order to not overly weight the most heavily cited papers nor lowly cited papers (Hirsch 2005). They concluded that the aggregate scientific impact of Keck Observatory exceeds that of the VLT, Gemini, or Subaru. Grothkopf et al. also show that WMKO has been significantly more productive than the other three observatories even when the different start-of-science-operations dates are taken into account.



	2003	2004	2005	2006	2007
CFHT	56	55	56	74	100
Gemini	26	26	38	54.5	60
JCMT	101	72	86	53	67
Keck	98	96	101.5	124	151.5
Magellan	38	27.5	24	38.5	40
Subaru	44	65	62	76	95
UKIRT	61	44	45	60	63
VLT	63.5	86	88.75	101	117.5

Figure 3: The number of refereed publications per telescope per year for various observatories (courtesy of Dennis Crabtree, Gemini Observatory).

6. Future Strategy

The next generation of extremely large telescopes (ELTs) is likely to complete construction and be commissioned circa 2020. Given the time required to conceive, design, build, and commission new instruments and adaptive optics systems, observatories operating today must consider the likely arrival of extremely large telescopes in their strategic planning. Keck Observatory has recently carried out an extensive scientific strategic planning activity with our user community. The two senior partners in Keck Observatory, Caltech and the University of California, are also

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founding partners of the Thirty Meter Telescope Project. Thus, the eventual arrival of ELTs is clearly in the minds of Keck Observatory management and users.

Keck Observatory and its user community are committed to maximizing the Observatory's scientific productivity up to and after the advent of ELTs. In general, the observing time on ELTs is expected to be in much shorter supply than on Keck. Therefore, both in the near term and after the advent of ELTs, Keck will remain a very valuable resource for our community to accomplish their scientific aspirations.

A number of strategies have been discussed in our strategic planning process to maximize the value of Keck to our scientific community in the ELT era. First, the Observatory must remain nimble to avail itself of scientific and technical opportunities. Because the ELTs will be much larger projects with many tasks required to achieve success and many partners, we aspire to preserve the nimbleness of a smaller, more focused organization. Keck Observatory also seeks to retain its strong, close relationship with our user community.

Another element of strategy concerns the types of observing programs that will be executed using Keck. Keck Observatory has carried out a number of large long-term observing programs, for example radial velocity surveys for planets (e.g., Wright et al. 2009), the Galactic Center proper motion program that has characterized the supermassive black hole (e.g., Ghez et al. 2008), and the DEEP2 galaxy redshift survey (e.g., Davis et al. 2003). We expect that the high demand for time on ELTs will render most programs relatively short in duration. Keck Observatory will likely support more large programs in the future in order to create unique datasets that result in high-impact scientific publications.

A new generation of wide-field imaging surveys is on the horizon (e.g., Pan-STARRS and LSST). In addition to producing well-defined surveys for objects over wide areas of the sky, these surveys will open up the time domain. Keck users were very quick to leverage the Sloan Digital Sky Survey to yield important new scientific results. Similarly, we envision Keck playing an important role in following up unique data sets revealed in these wide-field surveys. There will likely be a significant time-domain component to this follow-up. Modest investments in observing flexibility at Keck Observatory will be needed to support the growing profile and potential science impact of time domain astrophysics.

Keck Observatory's future scientific strategy recognizes that time on ELTs will be highly oversubscribed. Given the value of ELT time, we anticipate that a subset of future investigations carried out with Keck will study fairly large samples of objects. Only the most interesting of these objects would then be investigated in greater depth using an ELT. Thus, we expect that a many investigators will use an 8-10 meter telescope and an ELT as an observing system.

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Our future strategy recognizes that continued investment in science-driven instrumentation and adaptive optics systems is a necessity for maintaining Keck Observatory's scientific productivity and leadership. The 6.5 to 10 meter optical/infrared telescopes of today are the workhorses that will enable the scientific productivity of the optical/infrared community until the next generation of large telescopes are fully commissioned for science operations toward the end of the coming decade or perhaps in the subsequent decade. Even after the commissioning of GSMT, the 8-10 meter telescopes will play an important role for many years. Therefore, keeping the large telescopes in the U.S. observing system properly instrumented and taking advantage of advances in adaptive optics, detector, coating and other instrumentation technologies are crucial to the community's scientific productivity over the coming decade. The resources to build new, innovative instruments and adaptive optics systems need to be found in an era when there is strong demand for resources to construct the next generation of telescopes. One compelling reason for investing in instrumentation for the existing 8-10 meter telescopes is that such instruments can be brought into operation more rapidly than the next generation of telescopes. Thus, the scientific productivity of the optical/infrared astronomy community in the period 2010 to 2020 will be much more dependent on the operation of existing telescopes and the strength of their suite of instruments and adaptive optics systems than it will be on the next generation of ground-based optical/infrared telescopes. Because of limited resources and the modest time span before the next generation of telescopes is expected to come on line, Keck and the other large telescopes of today must make very thoughtful choices about the instruments and adaptive optics systems to be deployed in the near future and which science problems these systems will address.

Our scientific strategic planning process identified opportunities for new and enhanced instrumentation at Keck to contribute to our high scientific productivity and strategic positioning. The following types of instrumentation enhancement were identified for study and consideration for implementation in the future (beyond the initiatives already in progress described earlier in this article): high-efficiency optical integral-field spectroscopy; upgrading our wide-field optical spectroscopic capabilities; upgrading our infrared cross-dispersed spectroscopic capability with new detectors and possibly higher resolution; enhancing our precision radial velocity capabilities; and improving our ability to respond rapidly to time-sensitive phenomena, including rapid change of instrumentation.

Instrumentation for large telescopes has become more complex and ambitious due to the community-based scientific demand for sophisticated adaptive optics systems, enhanced multiplexing for wider-field multi-object spectroscopy at both infrared and optical wavelengths, and integral field unit spectroscopy with ambitious combinations of resolution and field of view. Instruments for large telescopes are

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costly and only likely to become more so as they increase in capability and complexity. Examples of ambitious instruments being designed and considered for implementation on large telescopes include the wide-field spectroscopic instrument WFMOS for Subaru and NGAO for Keck. NGAO has an estimated cost of $60 million, and HETDEX for the HET is estimated to cost $40 million. The typical cost of a significant, but not as ambitious instrument for an 8-10 meter telescope is of order $10 million.

Despite the relatively high cost of instrumentation for 8 to 10 meter telescopes, the costs are significantly lower than those for ELTs. Because of the high aggregate cost of ELTs and the cost of ELT instruments, in the reality of limited funding, ELTs are likely to have a rather limited number of instruments. Given the limited number of instruments an ELT will have and given the strong desire to manage overall risk in an ELT project, ELTs are likely to have a small appetite for assuming substantial risk in the design and construction of their instruments. All this is likely to encourage the ELT instruments to be general purpose and to use concepts that have already been demonstrated successfully on other telescopes. Therefore, truly innovative instrumentation is unlikely to deployed first on ELTs. Similarly, instrumentation that is fairly to highly specialized for a particular scientific goal is also unlikely to be selected for ELTs. This creates two opportunities for the current generation of 8-10 meter telescopes in the ELT era: 1) developing and testing truly innovative instrumentation and adaptive optics concepts that are sufficiently unproven to be impractical for ELTs; 2) developing and deploying instrumentation that is more optimized for a particular scientific area than is likely to be attractive to an ELT project. In both cases, this promises to create scientific productivity in certain niches for an 8-10 meter telescope where the ELTs are unlikely to dominate.

The capabilities of large-aperture interferometers will not be eclipsed by ELTs. Therefore, with their unique ability for extremely high spatial resolution, we imagine that the Keck Interferometer in the north and the VLT Interferometer in the south will remain scientifically productive and unique in the next decade and into the ELT era.

7. Acknowledgments

Members of the Keck Observatory management team and the Keck Observatory Scientific Steering Committee have contributed to the Observatory's scientific strategy and implementation, which this document describes. Figures 1 and 3 were graciously provided by Peter Wizinowich and Dennis Crabtree, respectively.

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