The Role of the W. M. Keck Observatory in U.S. Astronomy

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on behalf of the Keck Observatory and its scientific community[1]

For Astro2010 Study Groups: FFP and IPP

Executive summary

W. M. Keck Observatory is an essential element of the U.S. optical / infrared observing system. A significant fraction of U.S. peer-reviewed public access to large telescopes is achieved through Keck Observatory, specifically via NASA's partnership in Keck and through the NSF/NOAO TSIP program. Objective scientific productivity metrics reveal Keck Observatory to be a key source of U.S. leadership in astronomy. Keck Observatory is a successful public-private partnership in which limited federal funding is highly leveraged by state and private funding. We discuss policy enhancements that would help Keck Observatory realize its full potential in serving the U.S. astronomy community and functioning as an essential element of the U.S. ground-based optical/infrared system. Enhancements are recommended to the NSF/NOAO TSIP program and to NSF's ATI and MRI programs that we believe would benefit all non-federal observatories and the broad community that they serve. Open, peer-reviewed competition is advocated for all federal instrumentation investments.

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. 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.

2 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

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[1] Presented and discussed at meetings of the Keck Science Steering Committee with membership J. Brodie (UC Santa Cruz, Co-Chair), C. Martin (Caltech, Co-Chair), R. Akeson (NExScI), J. Cohen (Caltech), R. Ellis (Caltech), A. Filippenko (UC Berkeley), T. Greene (NASA), M. Liu (U. Hawaii), X. Prochaska (UC Santa Cruz), M. Bolte (UC Observatories, ex-officio), S. Kulkarni (Caltech, ex-officio), K. Glazebrook (Swinburne, observer), and P. van Dokkum (Yale, observer).

productivity. Figure 1 shows the number of refereed publications per year based on data obtained using the WMKO from 1996 to present (please note that the 2008 numbers are incomplete). 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.

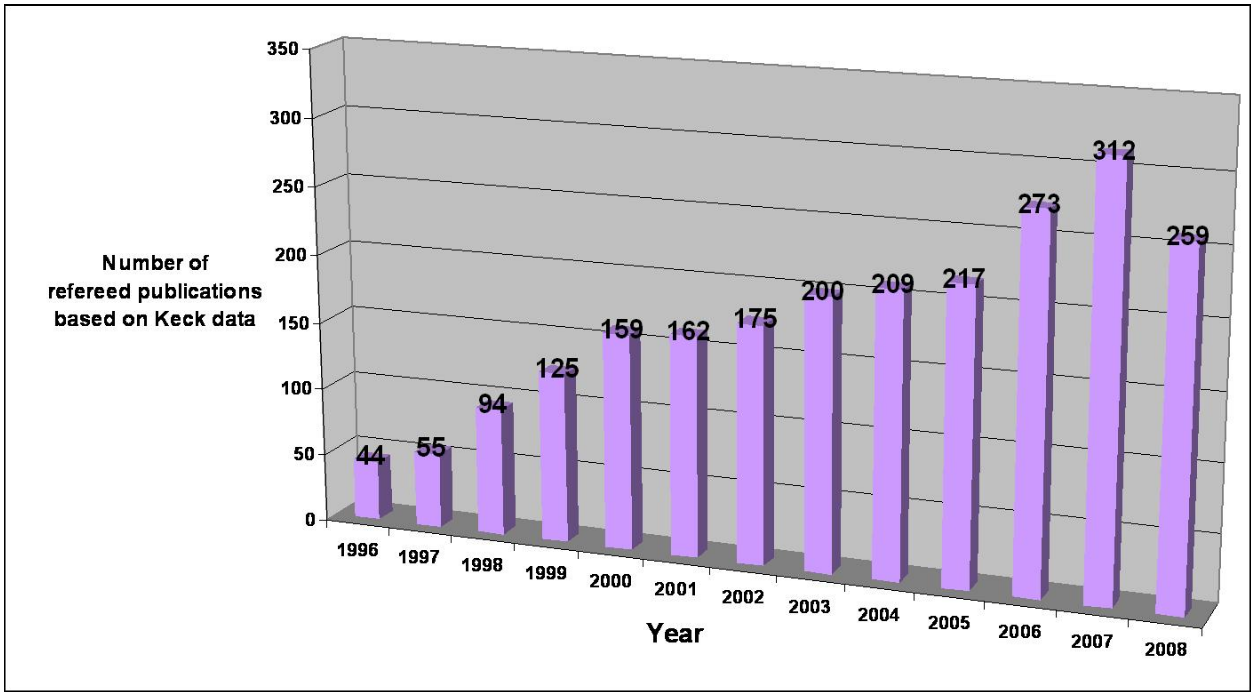
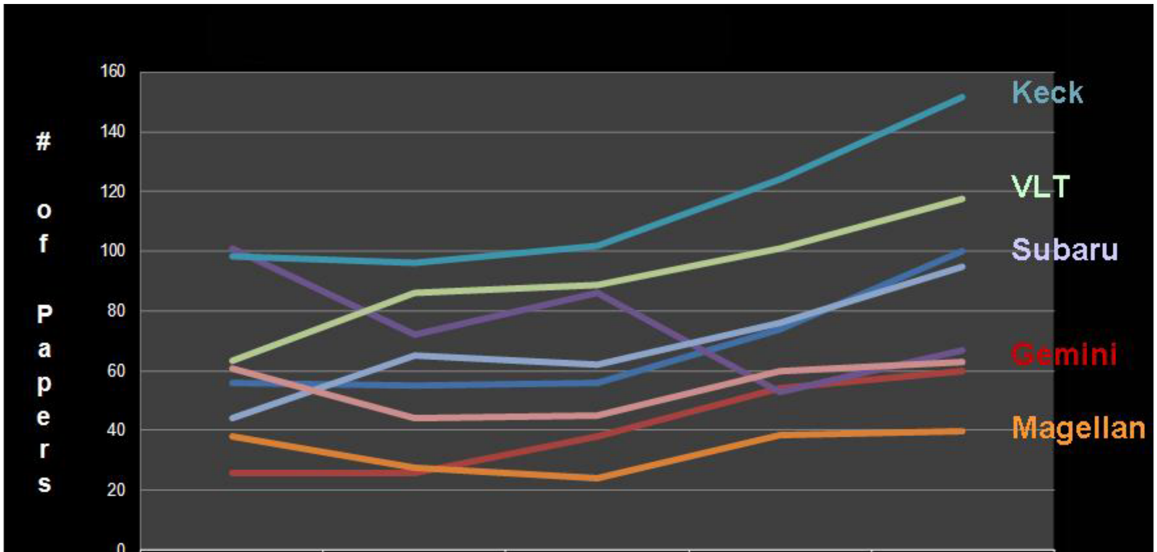


Figure 1: Number of refereed publications per year based on data from W. M. Keck Observatory. Note that the publication numbers for 2008 are incomplete.

Keck currently produces approximately 150 papers per telescope per year, which as shown in Figure 2, 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, SPIE, 7016, 40) 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., The Messenger, Volume 127, page 62, 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, J. E., 2005, Proceedings of the National Academy of Science, vol. 102, Issue 46, p.16569). As shown in Figure 3, they conclude 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 2: The number of refereed publications per telescope per year for various observatories from Dennis Crabtree (Gemini Observatory).

Many of the WMKO publications that form the basis for Figures 1-3 were written by lead authors not associated with U.C., Caltech, or U.H.; a significant percentage have no authors from these institutions.

Notable scientific results achieved using Keck Observatory and arising from NASA time allocations include: the discovery of dozens of extrasolar planets, including ones with masses less than that of Neptune; new information about the Uranus atmosphere and ring system from observations during the rare alignment of our line of sight and its ring plane; high-resolution spectra of comets revealing that comets contain a multitude of volatile organic compounds; and the Keck Interferometer spatially resolving gaseous and continuum emission in the protoplanetary accretion disks around 15 young stars. These NASA achievements are more fully described in the state-of-the-profession paper "The Value of the Keck Observatory to NASA and Its Scientific Community." Notable TSIP scientific results with Keck include: the study of optically thick absorbers near luminous quasars; the luminosity function of Ly-alpha emitting galaxies at high redshift; and the orbits and masses of extrasolar planets, particularly planets revealed by extensive transit observations.

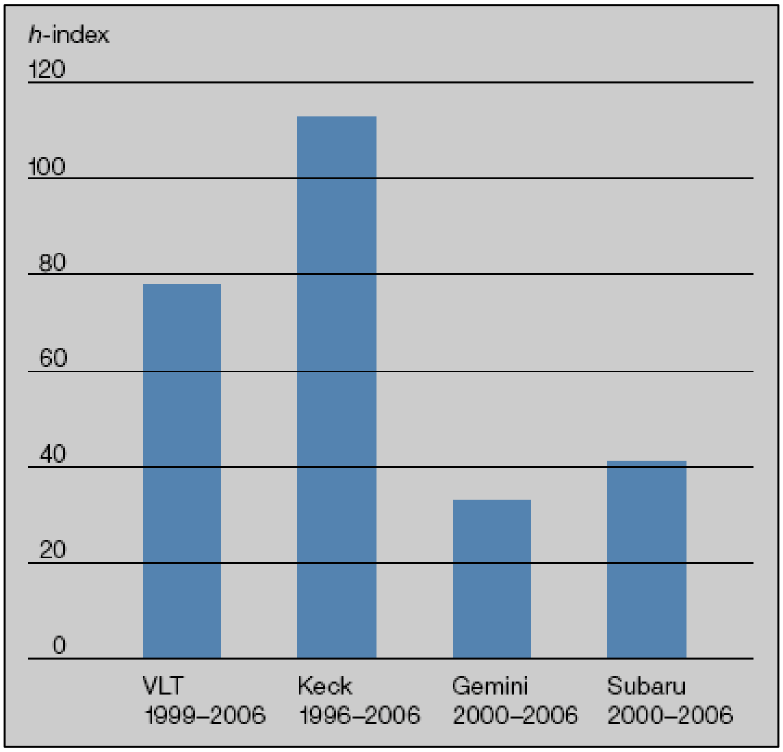


Figure 3: h-index for the VLT, Keck, Gemini, and Subaru observatories as of April 2007. A higher h-index implies higher overall scientific impact.

3 Current U.S. Community Participation in Keck Observatory

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 Hawai'i (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 (TSIP; approximately 24 nights per year; see Section 4). NOAO's recent ALTAIR committee noted in the context of 6.5-10 meter telescopes that "of the open access time available to the entire US community, Gemini represents ~57%, the NASA Keck time represents ~25%, and NSF TSIP represents ~18%." Thus, Keck Observatory represents a significant fraction of U.S. peer-reviewed public access to large telescopes.

Through specific time exchanges with both the Gemini Observatory and Subaru Observatory, the Keck observer community gains access to some of their instrument capabilities that are not emphasized at Keck and vice versa. For the Gemini exchange, the Keck community gains access to Gemini's mid-infrared instruments MICHELLE and T-ReCS (Keck has no non-interferometric mid-infrared capability) and the near-infrared instrument NIRI. The Gemini community gains access to HIRES, WMKO's high-resolution optical spectrograph. In the case of Subaru, the Keck community exchanges for access to Subaru's Suprime-Cam (wide-field optical imager) and MOIRCS (near-infrared imager and multi-object spectrograph). Note also that Keck, Gemini, and Subaru have a number of technical collaborations and that the three observatories cooperate on Mauna Kea infrastructure.

To measure the use of Keck Observatory by the broad U.S. community, we have studied the identities and institutional affiliations of principal investigators (PIs) and co-investigators (Co-Is) on Keck proposals from semester 2006A through 2009A. Principal investigators for WMKO observing programs were from 68 different institutions, 57 of which represent institutions not associated with Caltech, U.C., or U.H. Similarly, the co-investigators on observing programs came from 123 different institutions after excluding Caltech, U.C., and U.H. The total number of observing programs supported from semester 2006A through 2009A was 864. Of these, 238 programs (28%) did not have a Caltech, U.C., or U.H. PI. Similarly the NASA Keck programs from semesters 1996B through 2009A were conducted by 113 different PIs and 322 Co-Is at 122 institutions.

Given that Keck represents a significant fraction of U.S. peer-reviewed public assess to large telescopes, Keck is clearly an important tool for the broad U.S. community. When one considers also that the U.C., Caltech and U. Hawaii communities represent a significant fraction of U.S. ground-based observers, and the fact that they have collaborators throughout the country, Keck Observatory's role in the U.S. ground-based system is further amplified. Keck has been participating in the system road-mapping activities organized by NOAO (e.g., Workshops on the O/IR Ground-based System). Keck's Observer Newsletter and announcements are distributed to the broad U.S. optical/infrared observer community (including NASA and TSIP users), not only to Keck's partner universities' faculties. It is important for WMKO, our community of astronomers, TSIP staff and the funding agencies to fully recognize and capitalize on Keck's role as a crucial element of the U.S. ground-based system.

4 The Challenge of Maintaining the Scientific Productivity of Today's Large Telescopes

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 (GSMT and LSST) 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 European Southern Observatory is currently spending at a dramatically higher level for instruments and adaptive optics systems on their Very Large Telescopes (VLT) than the sum of all spending in the U.S. system on comparable large telescopes.

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 costly and only likely to become more so as they increase in capability and complexity. Examples of ambitious and expensive instruments being designed and considered for implementation on large telescopes include the wide-field spectroscopic instrument WFMOS (a Gemini / Subaru collaboration) and Next-Generation Adaptive Optics (NGAO) on Keck. Each of these instruments 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. As will be discussed below, ground-based instruments with costs in the $10M-$60M range are substantially out of scale with the NSF programs available to fund such instruments.

5 Telescope System Instrumentation Program

Keck Observatory has participated consistently in the Telescope System Instrumentation Program funded by NSF and managed by NOAO since its inception. TSIP has provided significant funding for two Keck instruments OSIRIS and MOSFIRE, and also for the NGAO preliminary design study. OSIRIS is an integral field spectrometer that provides simultaneous diffraction-limited imaging and R=3,900 spectroscopy behind the Keck II adaptive optics system. MOSFIRE is a near-infrared imaging spectrometer now being assembled and tested that will provide a field of view of 6.8′ in diameter for imaging and allow R = 3,000 spectroscopy with almost full band coverage in Y, J, H or K for 46 slits over a field of view of 6.1′ x 3′. NGAO is a transformational adaptive optics system currently being designed that will deliver unprecedentedly high Strehl, angular resolution, and PSF stability from red-optical to near-infrared wavelengths, through the use of multiple laser guide stars and atmospheric tomography.

In return for TSIP funding, NOAO has gained time on the Keck telescopes to allocate to the broad community (typically 24 nights per year; see Figure 4). Keck TSIP telescope nights have been the most heavily subscribed observing resource offered by the NOAO TAC; note the average oversubscription factor of 5.1 for Keck I and II reported in Table 2 of NOAO's ALTAIR Committee Report (http://www.noao.edu/system/altair/files/ALTAIR_Report_Final.pdf).

NOAO's ALTAIR committee which investigated community access to large telescopes reported that "the access to the additional capabilities on the non-federal facilities that is afforded by TSIP and the NASA open access time on Keck is highly valued by the community."

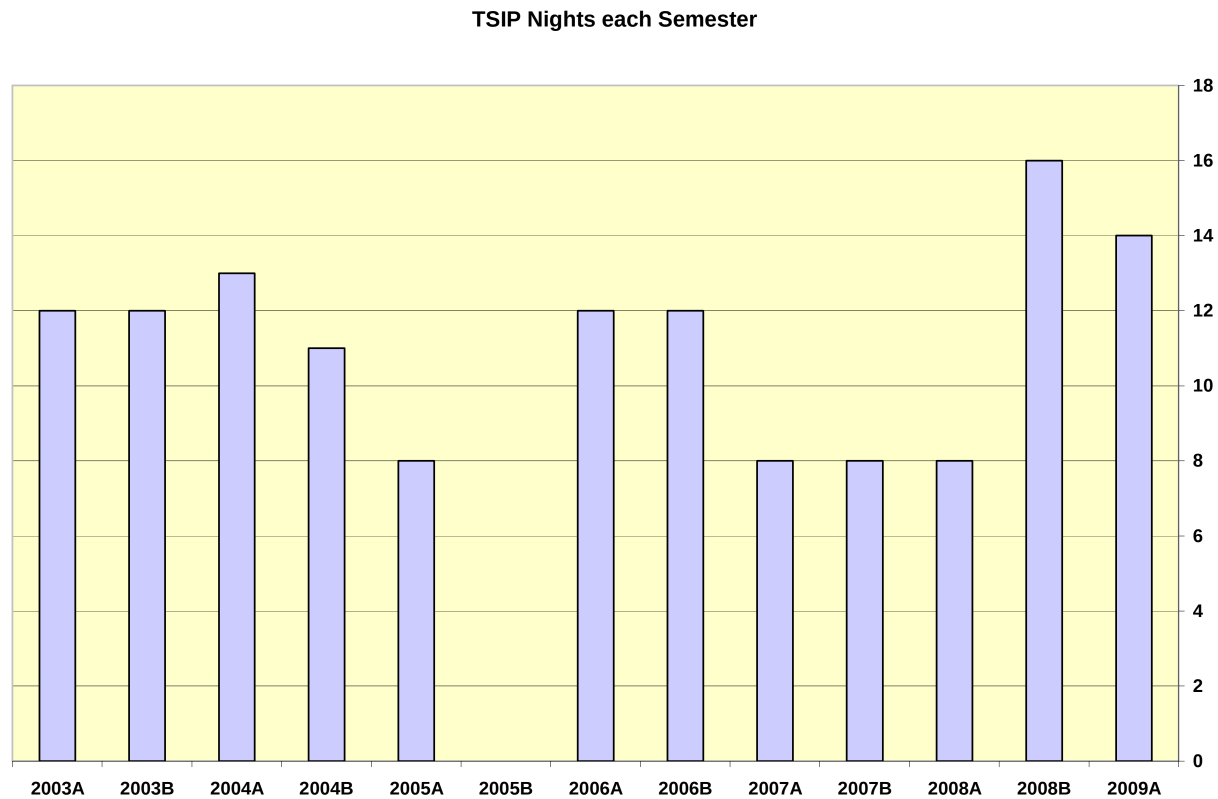


Figure 4: The number of Keck telescope nights allocated to TSIP each observing semester.

Figure 5 displays the instruments used by TSIP observers. Note that the two high spectral resolution capabilities, HIRES in the optical and NIRSPEC in the infrared, have been especially popular among TSIP observers. This is undoubtedly due to the relative lack of high-spectral-resolution capabilities on large telescopes in the U.S. observing system. In addition, Keck's leading adaptive optics systems were also used substantially, again because this is a relatively unique capability in the system. Multi-object moderate/wide-field optical spectroscopy (DEIMOS and LRIS) is another capability that was heavily used by TSIP, which is once again a fairly rare capability at large aperture in the U.S. system. Figure 5 indicates that TSIP users and the NOAO TAC are strategic in their use of Keck observing time, employing the access to carry out science that would be difficult or impossible elsewhere using public-access time.

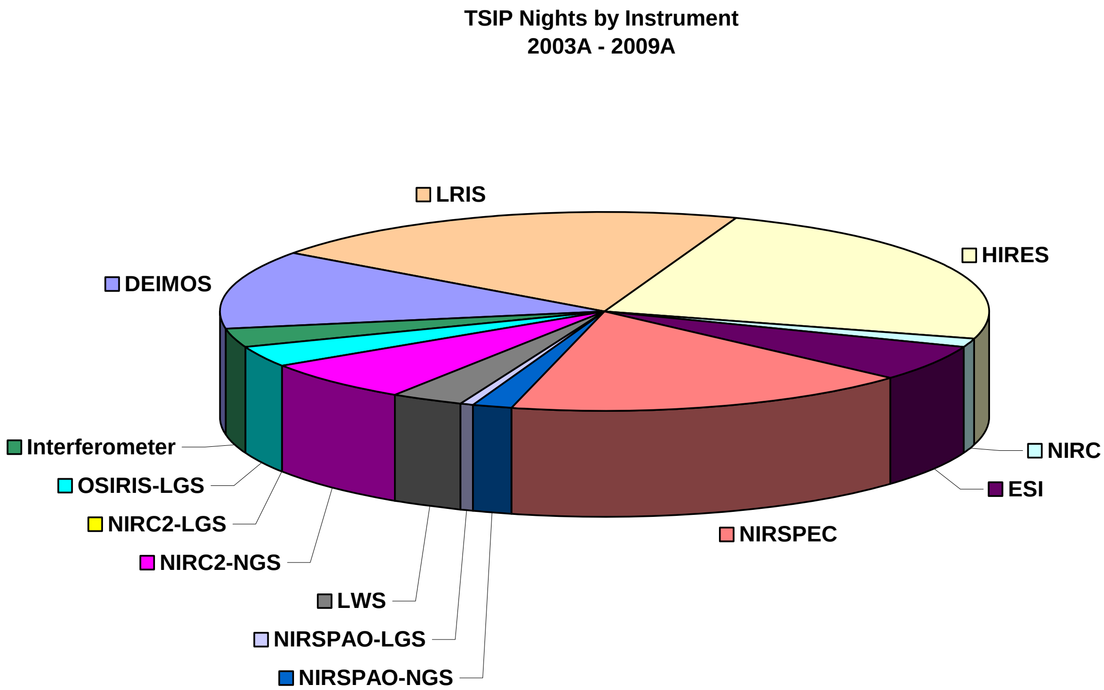


Figure 5: The distribution over Keck's instrumental capabilities of the TSIP observing time. Instrument descriptions are available at http://www2.keck.hawaii.edu/inst/index.php

TSIP has enabled Keck to develop innovative instrumentation and to offer it to the community, which would not have been possible without TSIP support. Based on the positive benefit to Keck Observatory, to the broad U.S. user community, and also to other private observatories, we urge the continuation and expansion of the TSIP program.

The TSIP program has not had uniform funding over time. For example, there was not a TSIP call for proposals in 2008, and as of this writing, TSIP has not been authorized to accept proposals in 2009. A stable TSIP program is critical to enable the development of major, new instrumental capabilities in the U.S. system. TSIP stability is also important for long-range budget and workforce planning at the independent observatories. Stability is perhaps even more important for the community seeking a consistent opportunity to propose for observing nights at non-federal observatories. We urge stable TSIP funding and regular TSIP proposal opportunities.

The ALTAIR committee recently made the following major recommendation: "To develop and expand the large telescope system, we recommend that NSF increase the funding, to $10M per year, for an NOAO-led TSIP or TSIP-like program in order to increase the open access time available on non-federal facilities." The implementation of this recommendation would help Keck Observatory achieve the role to which it aspires in developing science-driven advanced instrumentation and adaptive optics systems and making observing time available to the broad U.S. community. Note that the ALTAIR committee stated "when asked to prioritize possible avenues by which the large telescope system could by enhanced with any increases in federal funding, the highest priority of respondents was for more open access time on non-federal facilities."

ALTAIR also commented on the potential use of financial incentive factors in the calculations that convert TSIP funding into telescope nights. The ALTAIR report stated "We recommend additional flexibility in setting the incentive factors, e.g., to recognize the complexity of the instrumentation suite that the funding provides access to, to enable a longer-term time purchase agreement, or in seeking access to high-priority capabilities." Keck Observatory recommends that TSIP offer financial incentives for TSIP proposals that propose TSIP-defined high-priority capabilities and/or a long-term exchange relationship. We feel that the intended results of such incentives, creating long-term exchange relationships and prompting independent observatories to propose and then build instrumental capabilities that are needed for the optimal development of the U.S. observing system, are beneficial to both the proposing observatory and the broad U.S. user community.

6 Other Federal Support of Keck Observatory

The NSF-funded ATI, MRI and TSIP programs are the primary paths to funding instrumentation for U.S. ground-based faculties besides private philanthropy. The amount of funding in the NSF programs is modest given the escalating cost of state-of-the-art instruments for 8-10 meter telescopes. During calendar 2008, the average size of NSF-ATI awards was $290,000, with the largest award being $1.0 million. NSF MRI awards have a ceiling of $2-4 million (and require 30% matching contribution). These funding levels are significantly below the costs cited above for a typical new 8-10 meter infrared instrument of around $10 million and $60 million for a truly transformational capability.

We recommend that NSF encourage the funding of transformational instrumentation for 8-10 meter telescopes by carefully examining the funding limits and total allocations to the ATI and MRI programs. Establishing a mechanism to fund such proposals and addressing the tendency of review panels to seek to fund a greater number of smaller proposals would greatly aid the U.S. community that depends on such instrumentation to perform cutting-edge science.

The NSF and NASA occasionally fund "one-off" instrumentation activities at U.S. observatories, usually judging these proposals in relative isolation. One example is the funding of the Gemini "Aspen" instruments. We urge the NSF and NASA to conduct open competitions with opportunities for the full community to propose when considering funding any and all instrumentation activities. A community-wide activity that would define the science-driven needs of the U.S. optical/infrared system followed by various observatories proposing/competing to fill those needs is one possibility for addressing this situation. Such a process would allow the agencies have the opportunity to consider the full range of possibilities for developing and operating observing capabilities for the U.S. observing system, and Keck Observatory would welcome such a community-wide activity.

7 Keck Observatory as a Public-Private Partnership

Keck Observatory is a highly successful public-private partnership. The Observatory's initial construction was funded by a gift from the W. M. Keck Foundation to Caltech ($140 million in 1985 dollars). The Keck Foundation also funded much of WMKO's world-leading adaptive optics systems. Five sixths of WMKO's operations funding is contributed by the University of California and one sixth by NASA. Funding for new instrumentation has been obtained from grants from NSF and NASA, and also from donations by individuals and private Foundations.

Therefore, federal funding to Keck is highly leveraged by private and state funding. All of the partners, including the broad U.S. community who gain access through NASA and TSIP, benefit from the philanthropic gifts from the private sector that have enabled Keck's innovative telescope, powerful instrumentation suite, and world leading adaptive optics systems. For example, MOSFIRE is funded approximately 50% by NSF/NOAO TSIP funds and 50% by a private gift. The varied sources of funding that support WMKO make the Observatory relatively more stable against a shortage or disruption in any particular funding stream.

The U.S. community and associated investment of federal funds benefit from Keck's very cost-effective operations model. The ratio of operating cost to total invested capital is a standard metric of operational efficiency. By this metric, Keck has the lowest operating cost of major ground-based optical/infrared telescopes.

8 Summary of Recommendations

In order for Keck Observatory to realize its full potential in serving the U.S. astronomy community and functioning as an essential element of the U.S. ground-based optical/infrared system, we recommend that:

- NSF increase the funding, to $10M per year, for a TSIP or TSIP-like program in order to increase the open access time available on non-federal facilities;
- NSF make TSIP funding stable from year to year;
- NSF and NOAO implement financial incentive factors in TSIP to encourage high-priority capabilities and long-term exchange arrangements;
- NSF modify the financial limits and allocations in the ATI and MRI programs to enable proposals for developing transformational instrumentation for 8-10 meter telescopes;
- Planning and funding of new transformational instrumentation in the U.S. community be developed through a competitive process open to all participants in the ground-based optical/IR system.

9 Acknowledgments

Members of the Keck Science Steering Committee and Keck Observatory management team contributed to the formulation of this document and the ideas it contains.