Program **W. M. Keck Observatory**

Program Director Dr. Taft Armandroff, Observatory Director

Section One: Program Overview

[Section One – suggested 3 pages]

NOTE: The W.M. Keck Observatory is not an ideal fit to the PRG templates, being a facility that UC jointly manages with external partners under a separate contract. Some topics in the PRG template are more appropriately covered in the UCO PRG report and its appendices. That report is primary, with this on Keck as background.

The *W. M. Keck Observatory* (http://keckobservatory.org/) serves as the primary laboratory for astronomers from the eight UC campuses with astronomy programs, the Lawrence Berkeley National Lab, and Lawrence Livermore National Lab. As described below, UC is one of the two major founding partners and managers of the Keck Observatory, and UC astronomers have guaranteed access to 38% of the nights on each telescope. These nights are made available through a competitive proposal process run through UCO and scheduled in six-month blocks.

The W. M. Keck Observatory (hereafter WMKO) houses two telescopes, each with a 10-meter diameter primary mirror and equipped with state-of-the-art instruments used for research in astronomy and astrophysics at optical and infrared wavelengths. The Keck telescopes are widely regarded as the most powerful ground-based telescopes in the world and have been so since their completion in 1993 (Keck 1) and 1996 (Keck 2). The telescopes are located near the summit of Mauna Kea on the island of Hawaii, and the local headquarters is in Waimea, Hawaii. The Observatory has 116 staff members living in Hawaii.

The Observatory is managed via a partnership between the founding partners UC, Caltech, and NASA. The Keck Observatory capital costs were borne primarily by Caltech through two grants from the Keck Foundation of $70 M (1985) and $74.5 M (1992) and an additional ~$30 M from NASA. University of California buy-in to the project is through a contract that specifies that UC contribute 5/6 of the annual operations costs ($16 M) through March 2018. NASA contributes 1/6 of $16 M. In March 2018, UC will have paid the equivalent of the original Caltech capital investment. After this date, Caltech will take over ½ of operations costs, with UC maintaining the same 38% of the observing time on each telescope. In addition to the operations costs, the Observatory competes for external funding to upgrade instrumentation (including adaptive optics) and to build new instrumentation. The success rate in the NSF TSIP, MRI and ATI programs has been high ($33 M in grants from federal sources and ~$17 M from private sources have been raised for Keck instrumentation and adaptive optics since 1993).

The original design concept for the primary mirror in which hexagonal mirror segments were fabricated and a very precise sensor/actuator system was designed to hold them in place was revolutionary and developed by University of California scientists. The lead scientist for this development, Jerry Nelson (UCSC), was awarded a Kavli Prize in 2011 in recognition of this work.

The productivity of UC and other researchers from Keck Observatory is very high. Based on total papers published per telescope and total "impact" of the publications (using citation statistics, see Appendix 4), the Keck telescopes have been the most productive ground-based telescopes in the world for the past 20 years. The UCO PRG report lists a baker's dozen of *Greatest Hits* of UC optical-infrared astronomy over the last two decades (see Appendix 4 in UCO PRG report). The discoveries from Keck include some of the most profound and historically important scientific discoveries of the last 20 years. UC astronomers have been the recipient of an extraordinary number of international prizes including multiple Shaw, Gruber, and Kavli prizes, a MacArthur Fellowship, Crafoord Prize, Nobel Prize and the National Medal of Science. Most of the prizes awarded were based on work done at Keck. The UCO PRG report has additional information on esteem indicators to UC astronomers.

As judged by a recent External Review, the UC O/IR astronomy program is in the top-most tier of research universities in the US (UCO PRG report). Astronomers at UC and Caltech as a community, largely because of access to the Keck telescopes and instruments, compete successfully against nations and consortia of nations in this area of astronomy and astrophysics. This is all the more remarkable given that the large-telescope observatories that have been built and are operated at the national level typically have significantly larger operations budgets. For example, the Gemini Observatory, with two 8-meter telescopes (although the two are not co-located), was built and operated by a consortia of six countries

that includes the US federal government as a partner and has an annual operations budget that is just a little less than twice the Keck operations budget.

The *Keck Annual Report* lists annual publications based on data obtained with the Keck Observatory telescopes and also describes other highlights from each year. The last seven years of annual reports can be found here: http://keckobservatory.org/about/annual_reports.

Activity 1: Provide world-class observing capabilities to the Keck community.

Maintain the Observatory and its instruments to maximize its readiness and efficiency for nighttime observations. Provide the tools to effectively support proposal preparation, preparation for observations, and support for observations.

Activity 2: Participate actively in the development of new capabilities for the Observatory.

Regularly upgrading existing instruments and adding new instruments to the Observatory is crucial for continued research leadership. The instruments for the Keck telescopes are as important as the large primary mirror to the success of the telescopes. These are very sophisticated, large, and expensive projects ($5-15 M each). Starting with the first generation of Keck instruments, they have consistently set the world standard for large-telescope instrumentation. The instruments for Keck Observatory are primarily designed and fabricated in the UCSC, UCLA, and Caltech labs. However, the Observatory plays a very active and important role in seeking funding for new instrumentation, providing high-level management oversight of the instrument projects, ensuring that Observatory interface requirements are met, and planning for a smooth handoff of instruments into regular use. Adaptive optics is a key technology that has been identified for continuous improvement, and Observatory staff have played a significant role in its development and implementation.

Activity 3: Engage the public in the excitement of astronomy research.

The public outreach program of the W. M. Keck Observatory is extensive and diverse, ranging from activities in the Hawaii public schools, through outreach based on social media and press releases, to two public lecture series that are very well attended and have been running for more than a decade. One of the two lecture series has as a primary audience a number of individuals who have the capacity to make significant gifts to the Observatory. The Observatory regularly hosts film crews from around the world making science documentaries that highlight work of UC (and other) astronomers using the Keck telescopes. UC astronomers are in great demand presenting public talks and in K-12 classes each year describing their research done with the Keck telescopes. For more details on the use of Keck for outreach and teaching, see the Questionnaire results in Appendix 4 of the UCO PRG report.

Initiative 1: Next-generation adaptive optics.

The use of adaptive optics (AO) to correct atmospheric blurring and produce images limited only by the diameter of a telescope primary mirror was pioneered for astronomy at Lick Observatory. This technology was transferred to the Keck Observatory through a partnership between LLNL, UC, and the W. M. Keck Observatory. With adaptive optics, the Keck telescopes can produce images four times sharper than the *Hubble Space Telescope* for near-infrared wavelengths. The Keck Observatory with partners at the California campuses has been the undisputed leader in developing AO technologies, and astronomers using the Keck telescopes have been the world leaders in the use of AO for astronomy research.

Starting in 2008, a major design effort based on a partnership between the Keck Observatory, UC, and Caltech, has developed the conceptual design for a "Next Generation Adaptive Optics" system that will revolutionize AO-based observations. Realizing this new system is a major strategic goal of the Observatory.

Initiative 2: New capabilities through new instruments and significant upgrades of existing instruments.

Progress in astronomy and astrophysics is almost always driven by new observations. There are many examples of great strides forward being made after a new telescope or new instrument capability is developed and put into use by researchers. Superb instrumentation on the Keck telescopes is the prime reason why researchers using this facility have been so productive. However, because technology is continually advancing, the useful life of an instrument is typically

only ten years before it needs extensive upgrades or replacement. Thus, a continual program of instrument renewal is crucial to maintaining Observatory productivity.

At any time, a number of such programs are underway. The process by which projects are selected for conceptual design studies is a call for white papers for new instruments or upgrades. These are evaluated by the Keck Science Steering Committee (SSC) in the context of the Keck Scientific Strategic Plan, and a subset is selected for further development with some funding made available. The SSC makes a further down-selection after conceptual design studies are completed, and the best projects are approved to seek construction funding through proposals to federal agencies and/or foundations and private parties. These proposals are prepared by a team comprised of Keck Observatory staff and members of the UCO and Caltech instrument groups.

The most advanced of the current such programs is the Keck Cosmic Web Imager, an optical-wavelengths integral-field spectrometer led by Caltech that is optimized to work at very faint surface brightness levels. At less-advanced stages are projects to upgrade the detectors in two of the infrared instruments (UCLA IR Lab), a major detector upgrade for the 8-detector mosaic of DEIMOS (UCO-UCSC), a newly designed "deployable" tertiary that would allow rapid selection of any of the instruments at three different foci of the Keck 1 telescope (UCO-UCSC), and a spectrometer concept optimized for radial velocity studies of extra-solar planets (UCO-UCSC, UCB, and Caltech).

Initiative 3: Renewal of major infrastructure.

As the Observatory enters its third decade, some of the fundamental subsystems of the telescopes require rework, upgrades, and replacement. The most significant such projects are the design and implementation of the telescope control system including major upgrades to the encoding and pointing systems, reworking of segment support structures in the primary mirrors, and a new primary mirror control system.

Section Two: Alignment to Systemwide Principles

[Section Two – suggested 10 pages]

Principle 1: Act as one system of multiple campuses to enhance UC's influence & advantage.

Objective 1: Provide UC faculty, students and researchers with access to facilities, resources, and/or opportunities which position the UC system as a world leader in research, scholarship, and/or creative work.

The Keck Observatory is the most powerful ground-based optical/IR observatory in the world. UC faculty, postdoctoral, and graduate student access to this facility has enabled UC astronomy, as attested to by the recent UCO External Review, to be world-leading. No single campus would have had the resources to invest in a facility at this forefront. Keck Observatory is a poster-child program for the UC "Power of Ten".

Access to Keck is open to all qualified UC faculty and senior researchers at all eight astronomy campuses, LBL, and LLNL. Telescope time is awarded through competitive proposals that are read and ranked by UC peers. The time is fairly evenly distributed across the campuses after normalizing for the size of faculty.

Preferred access to Keck has allowed UC astronomy, physics/astrophysics, and planetary science programs to hire exceptional faculty. We have recently hired young faculty away from faculty positions at Princeton and MIT and successfully competed for junior faculty against Harvard. UC's access to Keck is also perhaps the primary reason for attracting top students into UC graduate programs in astronomy and astrophysics and for attracting postdocs to UC. Further information about the quality of faculty and the impact of UC O/IR facilities on recruitment and retention is in the UCO PRG report.

Objective 2: Enable successful competition for sponsored research projects and grants for which proposals from a single campus would not be competitive.

Access to the Keck Observatory has enabled UC astronomers to carry out research at the forefront and compete successfully for external funding to support that research. Certain sponsored research grants have been explicitly tied to Keck access (e.g., NSF support of the DEEP surveys, which received long-term LMAP status). Others are less directly associated, but there is no question that access to Keck, track records of research productively because of Keck data, and overall quality of UC astronomy and astrophysics faculty play a large role in attracting external funding in support of UC astronomy research. The details of sponsored research totals for the relevant groups are contained in the UCO PRG report.

In closing, we note that Keck is a major magnet for private giving. The Observatory itself was enabled by two gifts from the Keck Foundation in 1985 and 1991 totaling $144.6 M ($276 M in today's dollars), and success with Keck led to gifts by the Moore Foundation of $125 M to UC and Caltech that have launched the Thirty-Meter Telescope. A vigorous development program at Keck raises $0.5 M a year on average, with occasional peaks such as a grant of $5 M for the MOSFIRE spectrograph by Gordon and Betty Moore.

Principle 2: Promote efficient inter-campus collaborations & systemwide economies of scale.

Objective 1: Ensure efficient operation/management of shared resources, research results, facilities, systems, and/or staff.

Ensuring efficient operation of Keck Observatory is one of the responsibilities of the CARA Board, which is charged with oversight of the Observatory. Three of the six full members of the CARA Board are appointed by the UC President. Current UC members are Chancellor George Blumenthal (Vice-Chairman), Senior VP Nathan Brostrom, and UCO Interim Director Sandra Faber.

Highly-efficient nightly operations, measured by the fraction of "open shutter time", is one of the key objectives of Observatory operations. Starting a decade ago, sophisticated software tools were put into place in order identify the major sources of lost time (e.g., instrument faults, field acquisition, inefficient field identification) during the night, and resources were concentrated on improving the most significant issues. This is an ongoing program, but as of 2012, the Keck Observatory efficiency is among the highest for observatories worldwide with an "open shutter" goal of 80%.

Keck operates two 10-m telescopes on Mauna Kea, Hawaii. The annual cost is $16.0 M for operations and infrastructure (not counting new instruments, major repairs, or fund-raising/outreach), hence $8.0 M per telescope. The Gemini Observatory operates two 8-m telescopes, one on Mauna Kea and one in Chile. The cost computed in the same way is $30.3 M, or $15.2 M per telescope. Canada-France-Hawaii Observatory operates a 3.6-m telescope on Mauna Kea, Hawaii. Operations are $7 M/yr for this relatively small, solo telescope. The European Southern Observatory operates four 8-m telescopes in Chile. Operations in 2011 cost 16.9 M Euros ($24 M), plus 242 FTE. Converting FTEs to dollars using $100 k per FTE yields a cost of $48 M, or $12.0 M per telescope. Keck is operating its 10-m telescopes for ½ to 2/3 of the costs of other telescopes that are smaller and less complex. Despite Keck's lean approach, the CARA Board has mandated a thorough operations review, which will be the first in fifteen years. Results are expected in June 2013.

Finally, the processes for managing UC access to the Keck Observatory are efficiently handled centrally via UCO, two Time Assignment Committees populated by UC astronomers systemwide, and a software suite maintained by UCO staff.

Objective 2: Demonstrate systemwide research engagement and collaboration beyond that present on a single campus.

A formal program was established more than a decade ago to encourage multi-campus collaborations to use UC Keck time. This mechanism, Large Multi-Year Approved Programs (LMAP: http://www.ucolick.org/keckobs/lmap.html), has been used for four major projects involving PIs from between two and six UC campuses lasting five or more years. Outside of this formal program, applications from UC astronomers for Keck observing time commonly include investigators from two or more campuses. For the recent two semesters, ~30% of the science proposals for UC Keck time

involved investigators from two or more campuses. Approximately 50% of UC proposals also had collaborators listed from non-UC institutions; a significant fraction of these were international collaborations.

The UC instrumentation activities for developing and building new Keck instrumentation have not only been multi-campus in nature but have extended *beyond* the UC system. Because the laboratory/shop facilities are largely based at UCSC and UCLA, UC efforts are typically centered at one of these two campuses, with expertise in various technical areas and on the science teams drawn systemwide. However, Keck instrumentation is at the leading edge worldwide, and typical new instrument cost is >$5-15 M, with typical upgrades >$2 M. These very sophisticated optical/mechanical systems need to be extremely reliable. To build them, requires expertise not only within UC but also the larger Keck community, including Caltech, WMKO, and industrial partners. A history of Keck instrument partnerships is shown in Appendix 4 of the UCO PRG report.

Principle 3: Serve the State and citizens of California.

Objective: Collectively impact Californians through research in multiple regions of the state

An extensive answer is given to this question in the UCO PRG report. Here we add that Keck Observatory has its own vigorous public outreach program in Hawaii, with two public lecture series and additional engagement in K-12 school programs. These are supported in part by the Keck operations budget, but primarily through private contributions.

We stressed the role of high-tech astronomical science in burnishing UC's image in the public eye. As the ranking ground-based Observatory in the world, Keck has unequalled power to thrill and awe the public. The ability of UC astronomers to capture the media limelight is due in large part to the authenticity that Keck lends to everything we do. We also stressed the role of astronomy in publicizing UC in the international arena and competing for talented students, particularly in Asia. Again, it is Keck's prominence and location in Hawaii that give it this special power.

Section Three: Program Budget Narrative

[Section Three —suggested 2 pages]

Provide a brief narrative describing how UCOP systemwide funds are used to support the program's activities and initiatives (described in Sections One and Two).

Describe how your program distributes and prioritizes the UCOP systemwide funds by including a description of how your program would be impacted by the following UCOP budget scenarios.

Budget overview: UCOP systemwide funds were used in FY2011 (the fiscal year that the PRG Summaries are based on) to support 75% of WMKO's total basic operations and infrastructure renewal costs ($13,543,000) to provide world-class observing capabilities to the Keck community; the other 25% was provided primarily by NASA and from indirect cost recovery from federal grants. The majority of the basic operations and infrastructure renewal costs are salary and benefit costs comprising $10.0 M, of which UCOP funds $7.8 M. NASA funds most of the balance. Much of the operational procurements comprise summit and observing operations costs under the Laboratory and Facilities Renewal expenses sections on the PRG Summaries. General and administrative overhead encompasses 18% of total procurements. Outreach/Engagement/Education procurements are in WMKO's Public Information Office, supported by UCOP funds and by Advancement Department costs funded by external donations.

In FY2011, the UCOP funds supported 36% or $2.8 M of the total $8.0 M Observatory development programs. By "development", we mean activities that support new capabilities, such as instruments and adaptive optics technology. The majority of these programs are funded by NSF and NASA through grant proposals, or supported from foundation and donor contributions via fund raising campaigns. Many of the development procurements are sub-awards to UCSC, UCLA and Caltech labs for design and fabrication services. The $2.8 M of UCOP funds supported WMKO labor (46%) and equipment costs (50%) on these projects.

UC and NASA operations funding: The UC contributions are fixed by agreement—one portion (Keck 1) is augmented each year by the Consumer Price Index (CPI); the other portion (Keck 2) is augmented each year by the CPI with a lower limit of 4% and an upper limit of 6%. In FY2011, the total UC contribution was $12,558,000 and for FY2013 it is $13,414,000. NASA contributes approximately 1/5 of the annual UC contributions. In FY2011, this was $2,559,000 and for FY2013 it is $2,722,000 under the new NASA Cooperative Agreement effective 3/1/2013 for 5 years. NASA contributes approximately $610,000 annually on average to Observatory infrastructure renewal projects. NASA requested that the new NASA Cooperative Agreement include this additional funding as part of the operations total rather than separately funded. For FY13, that brings the total NASA Operations funding to $3,333,000 ($2,722k + $611k).

Night exchanges: Under the FY08-FY13 NASA Cooperative Agreement, NASA was given the option to exchange nights for $90,000 per night. Since FY2010, NASA has exercised this option for 22 nights through semester 2013B. WMKO uses these exchanges to fund needed infrastructure renewal projects such as the primary mirror segment repair project. NASA chose not to include this option in the new cooperative agreement, but if nights do become available, NASA could choose to exchange more nights at a similar rate. To further fund the segment repairs, beginning in FY2012 WMKO entered into a collaborative agreement with Yale University to annually exchange 5 science observing nights for the next 5 years at $96,600 per night.

Alternative budget scenarios: The base UC contributions to Keck Observatory operations are set by a contract between UC, Caltech, and NASA. It is therefore not appropriate to consider the -25% scenario.

For the +25% scenario, we have addressed the aspirations of the Keck Observatory user community, as clearly enunciated by our Science Steering Committee (SSC) and the CARA Board. The greatest science-driven need is for additional advanced instrumentation. The +25% scenario would be carried out in significant part between Keck Observatory and the expert instrument and adaptive optics labs in UCO. We specifically propose $1.75 M per year for the Next-Generation Adaptive Optics System, which would be developed in collaboration between WMKO and the adaptive optics team at UCO. We also propose $1.5 M per year for advanced development and upgrades of instrumentation on the Keck telescopes. This funding would be divided evenly between upgrading WMKO's NIRSPEC and DEIMOS instruments. NIRSPEC, which is a unique infrared cross-dispersed spectrograph, would be upgraded via a collaboration between WMKO and the UCO/UCLA Infrared Laboratory. DEIMOS, a uniquely capable multi-object optical spectrograph, would be enhanced through a collaboration between WMKO and UCO. Much of the funding in the +25% scenarios would be spent at UC campuses.

Finally, we note that the +25% scenario would raise the percentage of the WMKO budget devoted to new instrumentation and upgrades to approximately 20%. This would bring us in line with WMKO's chief competitor, the European Southern Observatory, whom we currently lag in this key metric of observatory renewal.

Program	**W. M. Keck Observatory**
Program Director	Dr. Taft Armandroff, Observatory Director

Appendix 3: Program Director Biosketch *[Director Biosketch not to exceed 1 page]*

Taft E. Armandroff is Director of the W. M. Keck Observatory. At the helm of operating one of the world's leading astronomical research facilities, his priorities are to advance the scientific objectives of the Observatory, strategically plan with the broad astronomical community, and develop resources that will sustain Keck Observatory's role at the forefront of astronomy for decades to come.

A 1982 graduate of Wesleyan University, Armandroff holds a B.A. in astronomy with high honors. He continued his studies at Yale University, earning an M.S., M. Phil., and Ph.D. in astronomy. As primary author or co-author of 41 refereed journal articles and review papers, he is a widely respected research astronomer in dwarf spheroidal galaxies, stellar populations in the Milky Way galaxy and nearby galaxies, globular clusters, chemical evolution of galaxies, and dark matter.

Prior to joining Keck Observatory in 2006, he worked for 19 years at the National Optical Astronomy Observatory (NOAO) in Tucson, Arizona, holding positions of Associate Director and Director of the NOAO Gemini Science Center. In that capacity, he spearheaded U.S. contributions to and scientific use of the international twin Gemini telescopes in Hawaii and Chile.

A leader of many instrument development projects in wide-field optical imaging, multi-object spectroscopy and infrared spectroscopy, he is a passionate advocate for new technologies that will assist astronomers in their quest to understand the Universe.

Armandroff serves on the Observatory Council of the Association of Universities for Research in Astronomy (management council for the National Optical Astronomy Observatory) and on the Mauna Kea Management Board of the University of Hawaii (stewardship body for the use of the Mauna Kea Science Reserve).

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Appendix 4: References and Key Publications

- Provide a list of relevant references and key publications from the most recent 3 years. Be sure to highlight any publications directly associated with initiatives or activities supported by UCOP funds.

Keck Observatory (all Activities and Initiatives)
Keck Observatory Annual Reports (all Activities and Initiatives)
Keck Observatory Scientific Strategic Plan (all Activities and Initiatives)
The MOSFIRE Infrared Spectrograph for Keck, illustrating the size and scale of typical Keck instruments:
McLean et al., Proceedings of the Society of Photo-Optical Instrumentation Engineers (SPIE), v. 8446, id. 84469J, 2012. (Activity #2; Initiative #2)
Keck Publications Compendium (Activity #1)
Keck 20th Anniversary Celebration (Activity #3)