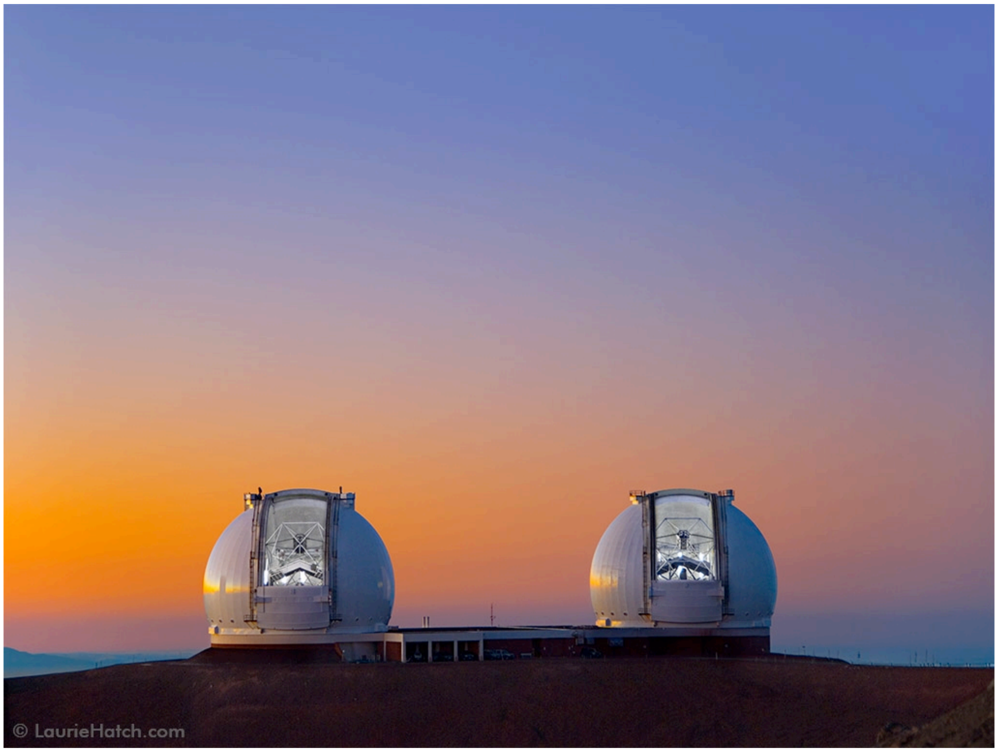
The W. M. Keck Observatory Scientific Strategic Plan 2009



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OVERVIEW

This short overview is intended as a stand-alone document summarizing the scientific priorities for the W.M. Keck Observatory for the next five years and beyond. It includes a brief scientific justification supporting the strategic plan as well as an overview of the process by which the Science Steering Committee, Observatory Management, and the community at large reached a consensus on this vision of the Observatory's future. Background information on the current state of the Observatory and the competitive landscape, a more detailed description of the science cases, as well as an in-depth technical overview, are supplied in the subsequent pages and are supported by four appendices.

In the Fall of 2008 the Keck Science Steering Committee (SSC) and Keck Observatory leadership began activities to revise the Scientific Strategic Plan (SSP) for the Keck Observatory. The previous SSP was created in 2003 and last updated in November 2005. Strategic planning activities provide the Keck community an opportunity to evaluate the state of the Observatory, review the broader astronomical landscape present and future, and focus on scientific opportunities in the coming decade. The SSP sets priorities in the annual and five-year planning and budgeting processes, and is used by the Keck Observatory Advancement Office to support their private fund-raising efforts.

Input from the community was solicited via teleconferences and a request for white papers that generated ~10 responses. In September 2008, a two-day retreat was held at the Beach House in Half Moon Bay. The participants were members of the SSC, the Observatory Directors, selected members of the Keck Observatory staff, three "at large" members of the UC and Caltech communities, two additional NASA representatives, and one additional representative from the University of Hawai`i (the number and affiliation of the additional representatives was chosen to numerically match SSC makeup and to broaden scientific and technical areas of expertise). All the participants and their affiliations are listed in Appendix 1. The agenda of the meeting and presentations are available at:http://www2.keck.hawaii.edu/plan08/index.html.

A draft SSP was circulated to the community at the end of 2008 and has been revised in response to comments and suggestions from observers at many institutions. We have closely coupled the Keck Scientific Strategic Planning process to the community-wide conversation enabled by the Astro2010 survey because Keck is a national resource for astronomical leadership. The current SSP document was thus further refined during the first half of 2009 to benefit from the Observatory's careful responses to the ASTRO 2010 Decadal Review.

1. Key Science Goals

The resulting priorities that define the Keck Strategic Mission for the next five years can be summarized as follows:

- High angular resolution astrophysics
- Faint object, high-precision and highly multiplexed spectroscopy from UV to K-band.
- Flexibility to exploit emerging opportunities
- Highly efficient operations

Keck has led the world in **high angular resolution astronomy**. Its pioneering Adaptive Optics system is mapping stellar orbits around the Milky Way's central massive black hole and has recently brought us the extraordinary first images of extrasolar planets. Keck will maintain its leadership role with the Keck Interferometer/ASTRA system (currently in development), with on-going updates to the existing Keck Adaptive Optics system, and with the Next Generation Adaptive Optics System (NGAO). The NGAO facility is being designed to satisfy a number of key science cases that require diffraction-limited performance at near-IR wavelengths, or modest Strehl ratios at red wavelengths, over narrow fields with high sky coverage and high sensitivity. The key NGAO science goals are: Understanding the Formation and Evolution of Today's Galaxies since z=3; Measuring Dark Matter in our Galaxy and Beyond; Testing the Theory of General Relativity in the Galactic Center; Understanding the Formation of Planetary Systems around Nearby Stars; and Exploring the Origins of Our Solar System.

Faint object, high-precision and highly-multiplexed spectroscopy with Keck has led to many major discoveries, including the vast majority of extrasolar planets discovered via reflex motion, the cosmological nature of gamma-ray bursts, and deep views into the processes of galaxy formation in the young universe. In the next several years we intend to provide new spectroscopic imaging capabilities that can discover and map IGM emission (Keck Cosmic Web Imager, KCWI), higher precision and more sensitive optical and near-IR spectroscopic capabilities that will stretch the boundaries of planet-finding and enhance synergies with upcoming IR and radio facilities, and enhanced capabilities for moderate and high resolution multi-object spectroscopy that will push the frontier of galactic archaeology and support the extensive follow-up demands of synoptic survey missions.

Keck's **flexibility to exploit emerging opportunities** has paid off in countless ways in the last 15 years. Keck users were very quick to leverage SDSS (e.g. z>6 QSOs), HST (z~3 galaxies), Scuba (z~2 sub-mm galaxies), and soon will pursue Kepler follow-up. In the next decade we anticipate a number of new survey missions (Kepler, WISE, Pan-STARRS, GAIA, NuStar, LSST, JDEM) and facilities (HST/SM4, JWST, ALMA, EVLA) that will benefit from present and targeted future Keck capabilities. Modest investments in observing flexibility will support the growing profile and potential science impact of Time Domain Astrophysics. Keck continues to provide a platform for testing new instrumental technology and observational techniques that greatly benefit the community at large and dovetail with plans for GSMT. We anticipate that Keck's role will evolve over the next 5-10 years, and that its flexibility, innovation, and survey power will remain unique strengths well into the GSMT era.

Highly efficient operations remain the cornerstone of Observatory scientific productivity. The top level goals for maintaining and improving effectiveness in this area are improved image quality, better throughput, maximizing the available observing time for science through more efficient procedures, less technical downtime and a significant and sustained effort in monitoring the performance of the telescope and instrument systems. We expect to develop techniques to further enhance system performance from an analysis of the data collected in the performance monitoring activity. A related activity is to improve cost efficiency through addressing areas that are particularly labor intensive: system setup, operation (e.g. aircraft detection, observing procedures) and maintenance.

2. Merged Scientific Priorities and Recommendations for the Next 5-10 Years

A set of merged priorities, categorized by cost into four tiers, was generated at the November 2008 SSC meeting based on the recommendations of three science panels (Planetary, Galactic, and Extragalactic) convened at the September 2008 Scientific Strategic Planning Meeting. Each panel was asked to identify and prioritize new initiatives for the Observatory for the next 5 to 10 years. The scientific drivers are summarized in the table in Appendix 2. These priorities were agreed to by the SSC in December and then circulated as part of the draft Strategic Plan document to the Keck community (UC, Caltech, Hawaii, and NASA). Town-hall teleconferences were held early in 2009 to solicit verbal feedback. Additional feedback was solicited from members of the astronomical community involved in the Decadal review. Final updates to the document and priorities were obtained at the February and July 2009 SSC and CARA board meetings.

Cost categories were delineated because WMKO will flourish only if high-profile new initiatives are balanced with a steady regard for the many smaller but no less vital elements that in combination maintain Keck as a leading astronomical observatory. Mega projects (>$20M) cannot be pursued without a major new source of funding, either private or government (or both). Large projects ($5-20M) will also require significant outside funding from private or government sources, but could in principal be accomplished only with government funding, especially if a new intermediate-scale opportunity is created by NSF. Medium projects ($1-5M) can be accomplished by combining TSIP, MRI, and ATI funds from NSF. Small projects (<$1M) can be completed with Observatory operations funds.

Items denoted by an X are those felt to have enough potential to warrant further study. They are included in their likely cost categories but are not prioritized with respect to each other or the listed projects. Targeted studies addressing strategic capabilities discussed in this plan and naturally led by WMKO community members should be solicited as part of the annual call for instrument concept studies. One or two new instrument concept or upgrade studies should be supported at the level of $100K per year.

Mega Projects

NGAO was the unanimous highest priority of the Planetary and Galactic Science Groups and the Extragalactic Panel sub-group considering high-resolution astronomy. NGAO will reinvent Keck and place us decisively in the lead in high-resolution astronomy. However, the timely design, fabrication and deployment of NGAO are essential to maximize the scientific opportunity. The advent of JWST (as early as 2013 but most likely after 2016) and TMT (2019?) will place a premium on NGAO obtaining the highest spatial resolution possible and also visible band capability. NGAO should be supported through PDR and every effort will be made to secure a "transformational" gift from the private sector to enable the project to proceed to the DD phase.

Table 1. Merged Priorities by Cost and Strategic Goal

Project Scale	Keck Strategic Goal				Study	Initiative [# = priority]
	HAR	FOS	HEO	Flex		
Mega (>$20M)	X					1. NGAO
Large ($5M-$20M)		X			X	Ultra-wide field spectroscopy
		X			X	DEIMOS upgrades
Medium ($1M-$5M)		X				1. KCWI
	X					2. ASTRA Ops
			X			3. Coatings
			X			4. TCS upgrades
		X			X	R>15000 MOS
		X			X	NIRSPEC upgrade
		X			X	Near-IR Radial velocity
	X				X	NIRC2 upgrades
Small (<1M$)			X			1. Complete MAGIQ
			X			2. Instrument performance monitoring
	X	X	X	X	X	3. Instrument concept/upgrade studies
				X		4. Innovative scheduling
	X					5. AO system upgrades

Blue indicates project already in the 5-year plan

HAR=High Angular Resolution, HEO= Highly Efficient Operations, FOS= Faint Object Spectroscopy, FLEX=Flexibility.

Large Programs

Keck holds a commanding lead in faint-object multi-object spectroscopy. DEIMOS, LRIS, and soon MOSFIRE will maintain this trend. A next logical step is to solidify this lead, particularly important for studying galaxy halos (including the Milky Way and M31) and a wide range of both near- and far-field extragalactic science, is to implement the originally planned second side of DEIMOS as well as to install state-of-the-art CCDs with enhanced blue-sensitivity on both arms. A design and cost study should be undertaken.

The advent of large synoptic surveys and the strategic targeting of Dark Energy science has created a need for massively multiplexed optical spectroscopy. While there has been a national effort to meet this need in the form of WFMOS, the future of this instrument is uncertain. Keck has ceded ultra-wide-field spectroscopy in the past and should continue to do so if WFMOS goes forward as a Japanese-led international effort. However, an opportunity may arise for the Keck community to access WFMOS via Keck/Subaru time-sharing. It may also be possible to access some of the priority science with a lower-cost approach, such as the DEIMOS upgrade. If WFMOS does not go forward, the study of ultra-wide-field spectroscopy options for the Observatory will naturally move to a higher priority.

Medium Programs

Keck has no capability for optical integral field spectroscopy (IFS). A flexible IFS spanning the 0.35-1 micron band would enable detailed studies of high redshift galaxies and their circum-galactic media, the co-evolution of gas inflows and outflows with forming galaxies, the first detection of IGM emission and recombination from reionization HII regions, the stellar populations of low surface brightness, low mass galaxies, and a host of other exciting science. The extragalactic panel found that the Keck Cosmic Web Imager (KCWI) filled this need at a modest cost and was its highest priority recommendation for faint object spectroscopy. KCWI should be the next seeing-limited Keck instrument.

Exploiting Keck Interferometer capabilities with ASTRA was the second highest priority of both the Planetary and Galactic panels. This capability is unique and support should be found for the relatively modest cost of KI on-going operations beyond the current NASA funding which ends in FY2010.

One study is currently underway for an upgrade to LRIS to provide R<15,000 multi-object capability. The need for additional studies was identified to evaluate/develop Keck's ability to carry out precision near-IR and optical spectroscopy for radial velocities, upgrade the NIRSPEC detectors, and upgrade NIRC2 detectors and optics.

Mirror coatings were a priority in the previous strategic plan. New capabilities are being developed at UCO/Lick and some are also commercially available for durable, broadband coatings. Implementing new technology coatings for the Keck primary, secondary, and tertiary mirrors remains a high priority.

Small Programs

The MAGIQ upgrades of NIRSpec and LRIS have been successful and future planned upgrades for other instruments (initially HIRES, DEIMOS) should be completed quickly. This should be linked to an enhanced program of telescope performance monitoring (TPM) that, coupled with instrument performance monitoring (IPM), will provide an end-to-end understanding of system performance, warn of problems, and point to future upgrades.

A systematic approach to IPM will pay dividends by both improving the understanding of extant data, warning of potential instrument degradation, and by delineating modest upgrades that could provide beneficial instrument improvements (better coatings, gratings, etc.) at low cost. WMKO management should work with the SSC and PIs in the community to construct a cost-effective instrument-monitoring plan.

All three science panels emphasized the numerous opportunities afforded by more flexible scheduling. These range from monitoring variable and moving sources with short, repeated observations, to implementing cross-institutional Key Projects. Currently being assessed are the cost and feasibility of building a new, smaller tertiary that would be automatically deployable (and hence retractable). It would feed the full FOV of all existing and planned instrumentation on the Keck I telescope. Such a device would better enable target of opportunity (ToO) observations, both for transient targets and objects where short cadence observations are desired over multiple nights. The TDAWG report should be revisited in the context of cost-effectiveness within the competitive landscape.

While NGAO remains our highest priority, targeted AO upgrades could yield near-term dividends. Ideally some could be synergistic with NGAO. AO upgrade opportunities should be revisited yearly until the NGAO development schedule is clear.

3. SUMMARY OF RECOMMENDATIONS

- *Targeted studies addressing strategic capabilities discussed in this plan and naturally led by WMKO community members should be solicited as part of the annual call for instrument concept studies.* One or two *new instrument concept or upgrade studies should be supported at the level of $100K per year*.

- *The timely design, fabrication and deployment of NGAO are essential to maximize the scientific opportunity.*

- *NGAO should be supported through PDR and every effort will be made to secure a "transformational" gift from the private sector to enable the project to proceed to the DD phase.*

- *A design and cost study should be undertaken to explore options for new capabilities in wide field multi-object spectroscopy.*

- *Keck should continue to cede ultra-wide-field spectroscopy if WFMOS goes forward as a Japanese-led international effort. If WFMOS does not go forward, the study of ultra-wide-field spectroscopy options for the Observatory will naturally move to a higher priority.*

- *KCWI should be the next seeing-limited Keck instrument.*

- *Support for on-going operation of ASTRA should be found beyond current NASA funding which ends in FY2010.*

- *Additional studies are needed to evaluate/develop Keck's ability to carry out/enhance precision optical and near-IR radial velocity capabilities, upgrade the NIRSPEC detectors, and upgrade NIRC2 detectors and optics*.

- *Implementing new technology coatings for the Keck primary, secondary, and tertiary mirrors remains a high priority*.

- *Future planned MAGIQ upgrades for other instruments (initially HIRES, DEIMOS) should be completed quickly. This effort should be linked to an enhanced program of telescope performance TPM) and instrument performance monitoring (IPM).*

- *WMKO management should work with the SSC and PIs in the community to construct a cost-effective instrument-monitoring plan.*

- *The TDAWG report should be revisited in the context of cost-effectiveness within the competitive landscape*.

- *AO upgrade opportunities should be revisited yearly until the NGAO development schedule is clear.*

STRATEGIC PLAN DOCUMENT

Background

Before developing some of the scientific rationales that underpin the strategic mission statement and priorities we provide brief summaries of the current state of the Observatory, its success in meeting its previous scientific objectives, and our view of the competitive landscape within which Keck must define itself going forward. Additional details, along with a glossary of terms and acronyms, are supplied as appendices.

1. Keck Observatory: 2009 Snapshot

In the 2003 Scientific Strategic Plan, the emphasis was on three areas: highly efficient operations, high-spatial-resolution astronomy and state-of-the-art instrumentation. The last of these was focused on maintaining the Keck Observatory lead in multi-object spectroscopy of very faint optical sources. That Plan described recommendations for increased Keck Observatory capabilities on a five-year timescale. The table in Appendix 2 lists the recommendations for increasing Observatory capabilities on a five-year timescale. Clearly, most of the previous plan's five-year recommendations have been accomplished.

Although there are now a large number of 6-10m telescopes, Keck has maintained the lead in research productivity. The figure below shows the number of refereed publications based on Keck data per year 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. Keck currently produces over 150 papers per telescope per year, which exceeds the scientific output of any other ground-based observatory. The impact of papers based on Keck Observatory data also significantly exceeds that of peer observatories. Crabtree (2008, SPIE, in press) showed that Keck Observatory has the most highly and extremely cited papers compared to our peers, and the fewest weakly cited papers compared to our peers. The peer group in this study includes ESO, Gemini, Subaru and HST. A study published in the ESO Messenger based on the h-index concludes that the aggregate scientific impact of Keck Observatory exceeds that of the VLT, Gemini, or Subaru.

There are six new capabilities recently commissioned or coming on line in the near future. The CCD in LRIS-R has been upgraded to a high-resistivity CCD with greatly improved sensitivity. MOSFIRE fills the need for multi-object highly efficient infrared spectroscopy. NIRES, providing full spectral coverage of the J, H and K bands simultaneously, is the near-IR equivalent of ESI. A new solid-state laser will be installed on Keck 1, with beam projection from behind the secondary, yielding laser-guide-star adaptive optics capability on both telescopes. New MAGIQ guiders with auto-focus capabilities for all instruments are being deployed. ASTRA will augment the Keck Interferometer with self-referenced spectroscopy, dual-field visibility, and narrow-angle astrometry modes. MOSFIRE is funded via a public-private partnership, combining public funds from the NSF/NOAO TSIP program with private funds from Gordon and Betty Moore. These instrumental advances keep Keck at the forefront of astronomical research.

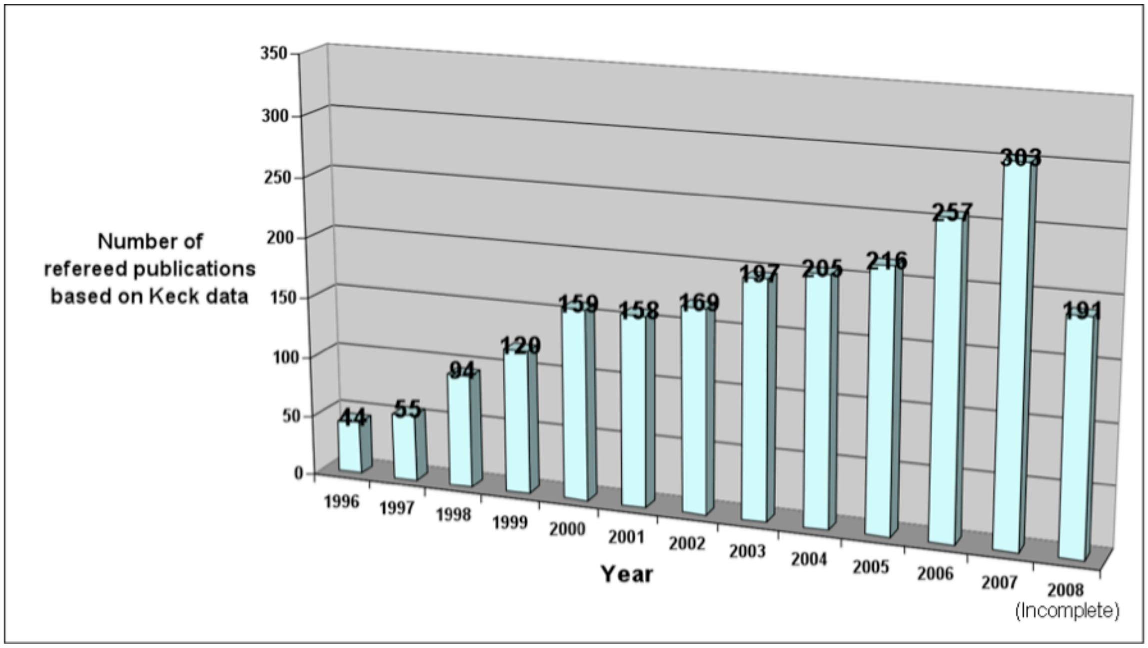


Figure 1. W.M. Keck Observatory Publication History

2. Astronomical Landscape: Science Opportunities & Competition

In 2009, there are ten fully-steerable optical/IR telescopes with an 8m or larger primary mirror. The Sloan Sky Survey has been largely completed and the success of the huge survey mode in astronomy is well established. PanSTARRS-1 is now in operation, and LSST and the TMT are scheduled to have first light within the next decade. In space, Kepler has already launched successfully, and WISE, GAIA and JWST are all scheduled to launch between 2009 and 2016. All of the space missions will provide a number of scientific opportunities for follow-up spectroscopy. JWST will provide observational capabilities, specifically imaging and R<3000 spectroscopy at wavelengths longer than 2μm that cannot be matched from the ground, even with the Keck telescopes and an advanced AO system.

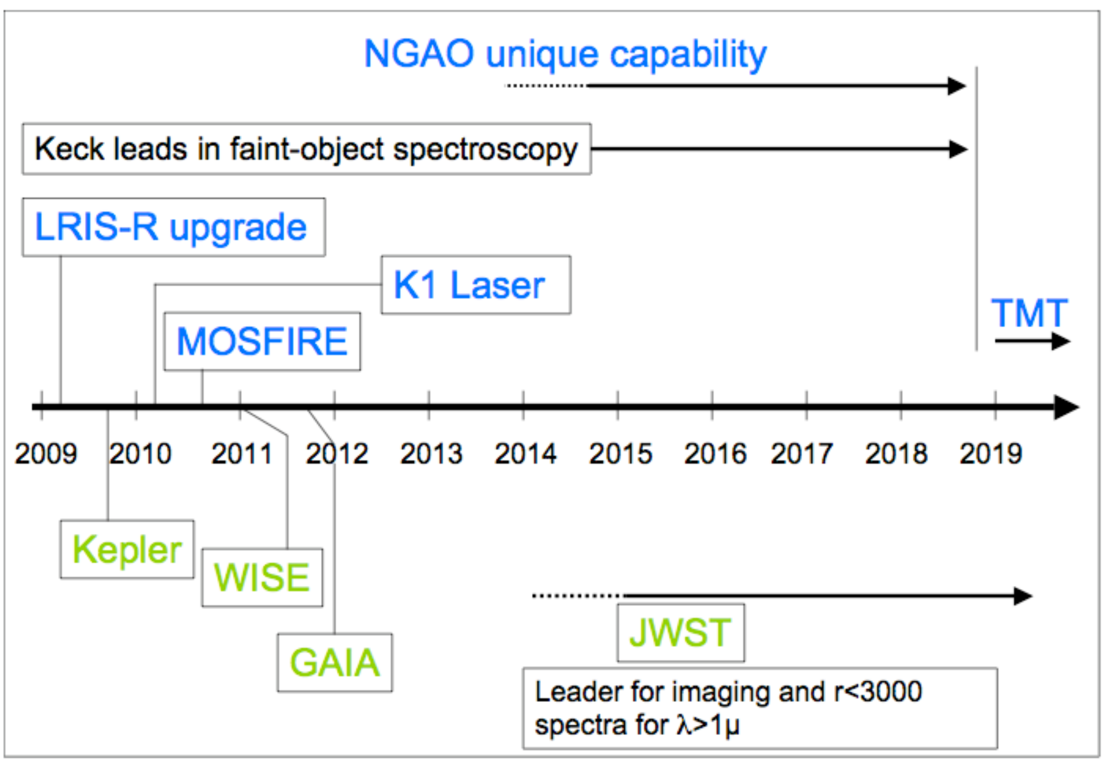
Space Missions

- *HST SM-4* installed two new instruments, Wide-field Camera 3 with enhanced UV, visible, and near-IR capabilities, and Cosmic Origins Spectrograph, an optimized UV high-resolution spectrometer. WFC3 surveys will yield new Near-IR targets that will need follow-up with MOSFIRE, OSIRIS, and NIRSPEC. COS will provide important new observations of the 0<z<2 IGM which will be complemented by Keck faint galaxy redshifts and by blue-optimized integral field spectroscopy.
- *WISE*. The Wide-field Infrared Space Explorer, to be launched late 2009, will perform a deep all-sky survey over 3-24 microns, with sensitivity 100-1000 times deeper than IRAS. It

will yield an enormous catalog of IR bright objects that includes everything from the nearest T-dwarfs to the most distant and luminous ULIRGs. A close collaboration between WISE and WMKO is natural because of the leading roles of UCLA and Caltech/JPL in both observatories.

- *Kepler* is targeting 150,000 stars in 100 deg^2 in Cygnus for planetary transits. Kepler is sensitive to orbital periods from a few hours to years, and planets ranging from gas giants to Earth-like planets in the habitable zone. Transit candidates, that will be comparatively faint (V<12) stars, will require radial-velocity follow-up from Keck.
- *GAIA* (launch 2011, catalog released 2019) will provide a superb astrometric reference grid that will support major advances in WMKO relative astrometry using AO.
- *JWST* (launch 2013-15). The James Webb Space Telescope will become the supreme facility for deep, diffraction-limited near and mid-IR imaging and low-to-moderate resolution spectroscopy. At 2 microns, JWST will be >200 times faster than Keck for imaging and significantly faster for spectroscopy even between OH lines, unless aggressive pre-spectrometer OH-suppression is implemented. JWST will provide coronographic capability, multi-object spectroscopy and integral-field spectroscopy (1-5 microns). While nominally covering the 0.6-28 micron range, JWST will not be diffraction-limited blueward of 2 microns.

Figure 2. Astronomical Landscape. Competition & Opportunity to 2010.



Ground-Based Facilities & Surveys

- ALMA will revolutionize mm-wave astrophysics with high resolution (0.05-1") spectroscopic imaging of CO, CII, thermal and non-thermal continuum, and molecules in a vast variety of sources from nearby proto-planetary systems and young stars to distant star-forming galaxies and AGN. Keck will complement ALMA in equatorial targets with high-resolution imaging and imaging spectroscopy on similar spatial scales.
- UKIDSS/VISTA is producing catalogs of millions of near-IR sources that will require spectroscopic follow-up with emphasis in the near-IR.
- Palomar Transient Factory and Pan-STARRS-1 are about to initiate the era of Time Domain Astrophysics. They will be followed by a series of new imaging surveys and synoptic, wide-field capabilities (One-Degree Imager, Dark Energy Survey, HyperSupremeCam, and in 10-15 years, LSST). These vast new catalogs will generate an endless supply of transients, variables, astrometrically- and photometrically-selected objects that require follow-up spectroscopy and high-resolution imaging. Keck can position itself to exploit these fire hoses of new data.
- The massively multiplexed spectroscopic survey (MMSS) SDSS has and will generate many new discoveries, some based on Keck observations. The main new such survey, WFMOS, is yet to be approved, but could generate a large payoff in new science from galactic archeology to galaxy evolution to cosmology. An important question for Keck is what role to play in the inevitable future 8-10 m MMSSs.
- The ambitious future plans for the VLT, the Large Binocular Telescope, and the Gran Telescopio Canarias (GTC) represent the most direct competition to the Keck Observatory. Keck must pick its areas for competition carefully, remain nimble, and quickly exploit scientific and technological opportunities.
- TMT (as well as EELT and GMT) weigh heavily in the 10+ year horizon of Keck. Keck has only a few more years to position itself for the ELT era. Should Keck reinvent itself as a survey facility? Should Keck become a feeder telescope? Should it emphasize diffraction-limited optical imaging and spectroscopy?

Science Drivers

1. Science Enabled by New Capabilities in Very High Angular Resolution Astronomy

1.1. NGAO

Galaxy Assembly and Star Formation History

At redshifts of $z \sim 1 - 3$ galaxies are thought to have accumulated the majority of their stellar mass, the rate of major galaxy mergers appears to peak and instantaneous star formation rates are consistent with those of local starburst galaxies. Given the high level of activity at these redshifts transforming irregular galaxies into the familiar Hubble sequence of the local universe, it is of strong interest to study these galaxies in an attempt to understand the overall processes of galaxy formation and the buildup of structure in the universe.

The global properties of these galaxies have been studied in detail, however little is known about their internal kinematics or small-scale structure, particularly with regard to their mode of dynamical support or distribution of star formation. AO and seeing-limited observations suggest that the kinematics are frequently inconsistent with simple equilibrium disk models. However, spatially resolved information for a larger sample is needed to conclusively determine whether the majority of star formation during this epoch is due to rapid nuclear starbursts driven by large-scale merging of gas-rich protogalactic fragments, circumnuclear starbursts caused by bar-mode or other gravitational instabilities, or piecemeal consumption of gas reservoirs by sub-kpc-scale star forming regions in stable, rotationally-supported structures. *NGAO's increased sky coverage will vastly expand the number of available targets for this study.*

Figure 3 shows simulated IFU-derived images and velocity fields for a galaxy merger observed with current Keck LGS AO (left) and NGAO (right). With NGAO, images similar to the kinematic map in the lower right panel will also be derived for star formation rates, metallicity distributions, velocity dispersion, and age, thus allowing us to address the issue of whether the observed peak in star formation at z ~ 2.5 is stimulated by galaxy mergers. While JWST will be more sensitive for extremely high redshift galaxies (due to larger IFU spaxels and lower IR backgrounds), *NGAO's higher spatial resolution will provide more detailed information regarding the structure and kinematics of galaxies on sub-kpc scales.*

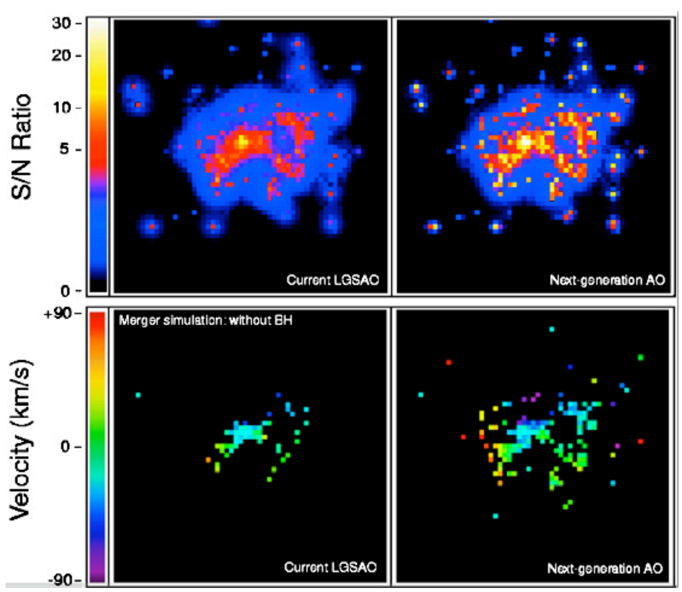


Figure 3. Improvements in SNR and velocity measurements with NGAO. Top: Hα emission line SNR for a galaxy merger at z=2.2. Using current Keck LGS AO (left) there are only a few pixels with SNR≥10 (yellow), but with NGAO (right) there are an order of magnitude more such pixels. Bottom: Kinematic maps for the same cases as the upper panels, showing velocities for those pixels with SNR>5. Note the difficulty with current LGS AO of determining whether the lower left panel is kinematically differentiated from a typical ordered rotation map with smooth transition across the galaxy from red (positive velocities) to violet (negative velocities). The NGAO panel brings out the spatially complex velocity field which characterizes a major merger. (Simulations courtesy D. Law, UCLA)

Supermassive Black Holes and Active Galactic Nuclei

During the past several years it has become increasingly clear that black holes (BH) play a key role in galaxy formation and evolution. The most important evidence for a close connection between BH growth and galaxy evolution comes from the observed correlations between BH mass and the bulge velocity dispersion of the host galaxy (the "M_{BH}-σ_* relation"). Despite the fact that BHs contain only about 0.1% of the mass of their host bulge, their growth is evidently constrained very tightly by the kiloparsec-scale properties of their environment.

Key observational goals in this field that Keck NGAO will address include:

- demographics of BHs in nearby galaxies over a wide range in BH mass
- investigations of the redshift evolution of the M_{BH}-σ_* relation
- studies of the host galaxies of AGNs out to high redshifts

Several Astro2010 white papers list these goals as priorities for the next decade. Since the minimum detectable BH mass scales as ~ distance * (angular resolution), *NGAO will be able to detect lower mass BHs to farther distances than JWST*. NGAO will place important constraints on the slope of the M_{BH}-σ_* relation and will likely double the number of galaxies with kinematics-based detections of massive BHs before TMT first light. In the era of TMT, NGAO-based observations will remain crucial for screening the best low-mass candidates and improving the statistics for understanding the amount of intrinsic scatter in the M_{BH}-σ_* relation.

The expected performance of NGAO at the Ca II triplet (850 nm) will enable the detection of a 10^7 M_{Sun} BH at the distance of the Virgo Cluster (17.6 Mpc). To date, only a handful of similar mass BHs have been detected kinematically, and all of them at distances of only a few Mpc. We expect a few thousand new supermassive BH targets will be within reach of 10m-class telescopes that are diffraction limited to visible wavelengths.

In addition, AO observations in the near-IR will be used to study quasar host galaxies at high redshifts. With the much higher Strehl NGAO system, improved contrast levels between the bright QSO and the faint host galaxy will enable spatially resolved studies of stellar populations and emission-line kinematics. These results will shed light on the interplay between AGNs and their hosts, including the role of AGN feedback in shaping galaxy formation and evolution.

Testing General Relativity in the Galactic Center

The proximity of our Galaxy's center (GC) presents a unique opportunity to study a massive BH and its environs at extremely high spatial resolution. In the last decade, orbital motions for several stars near the GC have revealed a central dark mass of 3.7 x 10^6 M_{Sun}, and constrained the GC distance, R_0, to within a few percent. Since R_0 sets the scale within which is contained the observed mass of the Galaxy, measuring it to high precision enables one to determine to equally high precision the size and shape of the Milky Way's dark matter halo and illuminates the process of galaxy formation (how the dark matter halo relaxes following mergers).

Though the current orbital reconstructions in the central 1"x1" are consistent with pure Keplerian motion, with improved astrometric and radial velocity precision, deviations from pure Keplerian motion are expected. With NGAO we will be able to detect these deviations due to a variety of effects, providing a unique laboratory for probing the extended dark matter distribution of the GC, and *testing general relativity for the first time in the high-mass, strong gravity, regime*. NGAO will measure these non-Keplerian motions to precisions that will not be greatly surpassed even in the era of extremely large (~30m) telescopes, and will be able to continue long-term monitoring campaigns that may be too costly to perform on larger telescopes.

In addition to reduced source confusion, NGAO will improve measurements at the GC through:

- Detection of new stars whose orbits will improve the precision of measurable GR effects.
- Decreased field dependence of the PSF, increasing photometric and astrometric accuracy.
- Increased SNR will improve the radial velocity contribution to orbit determinations.

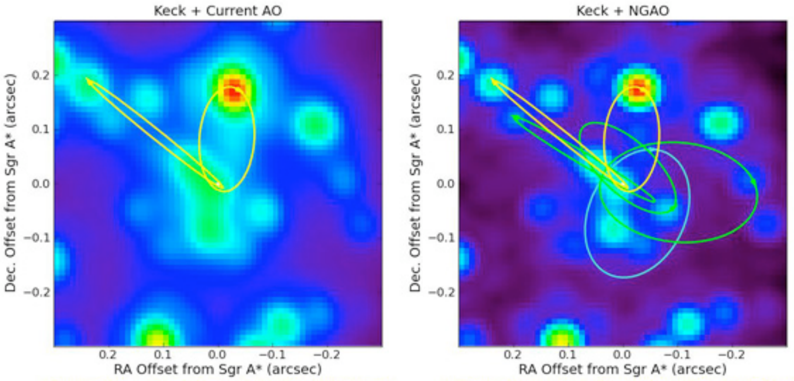


Figure 4. Comparison of orbital measurements at the Galactic Center with current Keck + LGS AO (left) and NGAO (right). (credit:www.astro.ucla.edu/ ~ghezgroup/ gc/pictures/Future/GCorbits.

Imaging and Characterization of Extrasolar Planets Around Nearby Stars

The unique combination of high-contrast near-IR imaging and large sky coverage delivered by NGAO will enable direct imaging searches for Jovian-mass planets around nearby young low-mass stars and brown dwarfs. The "extreme AO" systems being designed at Gemini and ESO are very powerful planet-finding instruments, but their design restricts them to searches around bright, solar-type stars (I<9). NGAO provides an important complementary approach. Establishing the mass and separation distribution of planets *around a wide range of stellar host masses and ages* is a key avenue to understanding the planet formation process.

By number, low-mass stars ($M \leq 0.5M_{Sun}$) and brown dwarfs dominate any volume-limited sample, and thus these objects may represent the most common hosts of planetary systems. While such cool, optically faint targets will be unobservable with extreme AO systems, thousands of low-mass stars in the solar neighborhood can be targeted by NGAO because of its LGS. Direct imaging of extrasolar planets is substantially easier around these lower mass primaries, since the required contrast ratios are smaller for a given companion mass.

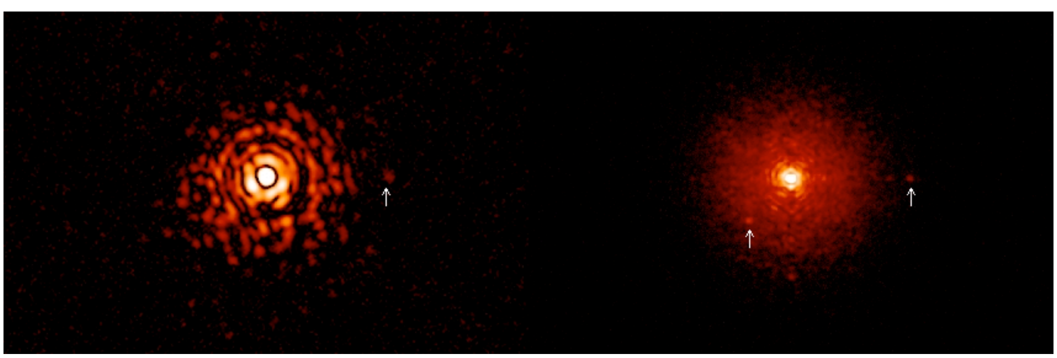


Figure 5. NGAO's direct imaging ability (right image) to detect faint companions around nearby stars versus the current Keck LGS AO performance (left). The images are 150 sec J-band integrations. The first companion with $\Delta m = 7.1$ is located at 0.6" (at 3 o'clock) from the primary (G2 star with V=17 and J=15.8). The second companion with $\Delta m = 6.0$ is located at 0.3" (at 7 o'clock). The first companion is detected with both AO systems while the closer one is only visible with NGAO's improved sensitivity and angular resolution. NGAO's planned coronagraph coupled with detection techniques will further improve the companion sensitivity by ~ 3 magnitudes.

Direct imaging and spectroscopy of extrasolar planets with NGAO will allow us to:

- Measure physical properties (color, temperature, luminosity, surface gravity) and test theoretical models of planetary evolution.
- Characterize their atmospheres (water and methane absorption lines).
- Expand the sample of resolved systems and push to cooler, lower-mass systems.

Debris Disk Demographics and Substructure

Debris disk systems represent the extrasolar analogs of the asteroid belt and Kuiper Belt in our own solar system. Spatially resolved high-contrast, multi-wavelength imaging offers a unique opportunity to study their circumstellar material and their embedded low-mass planets. Key questions that NGAO will address include: (1) How do primordial planet-forming disks transition into debris disks? (2) What is the role of planets in this transition? (3) How do planets interact with the disks in which they are embedded?

NGAO's unprecedented angular resolution and stable PSF will extend direct imaging surveys to distances >100 pc yielding a much larger sample of resolved debris disks. This will allow for comparative studies of debris disk properties (sizes, substructures, grain properties) as a function of stellar host mass, age, environment, etc., thereby *offering a comprehensive external view of what the young solar system may have looked like*.

In addition, high resolution NGAO **optical** imaging will enable scattered light imaging studies off the sub-micron sized dust grains. This new, powerful capability is particularly important in the post-HST era, as it can reveal dynamical signatures (rings, gaps) in disks due to embedded planets out to three times greater distances than previous studies and over smaller physical scales around nearby systems.

1.2. Phase Referencing and Astrometric Science with the Keck Interferometer

The NASA-funded Keck Interferometer is being further developed with NSF MRI funds to extend its capabilities to a much broader range of science by providing higher spectral resolution, a significantly fainter limiting magnitude and a narrow-field astrometry mode. The following four science cases are the drivers for this ASTtrometric and phase-Referencing Astronomy (ASTRA) project which relate to the new ASTRA observing modes (Figure 6).

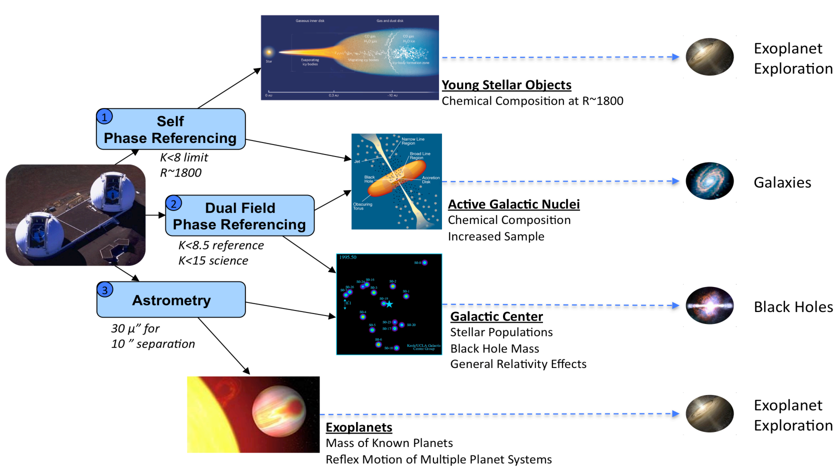


Figure 6. The ASTRA operating modes (self phase referencing, dual field phase referencing and astrometry) and the science cases for which they are being developed.

Terrestrial planet forming region of proto-planetary disks. By increasing the near-infrared spectral resolution of the interferometer, it becomes possible to study the chemical composition and the planet formation mechanisms in young stellar objects. ASTRA has provided an R~1800 spectral resolution mode in the K-band that is operational and is being used for science (higher resolutions are possible for future upgrades).

Milliarcsecond-scale unification of Active Galactic Nuclei. The planned ~ 5 magnitudes improvement in the sensitivity of the interferometer will increase the size of the sample of observable AGNs. A more systematic study of the role of the torus in the unification of AGNs will become possible on a representative sample.

Masses and orbital inclination of known exoplanets. The planned 50 to 100 micro-arcsecond astrometric capability, when combined with existing radial velocity measurements, will allow the mass and orbital inclinations of known planetary systems to be determined independently. Figure 7 is a plot of known radial velocity planets where the astrometric signature would be large enough to be measured with ASTRA and suitable reference stars have been identified (this sample will increase as more planets and reference stars are identified).

High-order general relativistic effects in the Galactic Center. Current adaptive optics observations have delivered accurate measurements of the orbits of the stars around the black hole at the center of our galaxy, yielding mass and distance measurements. With the increased astrometric accuracy (30 micro-arcseconds for this science case) the Keck Interferometer will enable the first measurements of high order general relativistic effects.

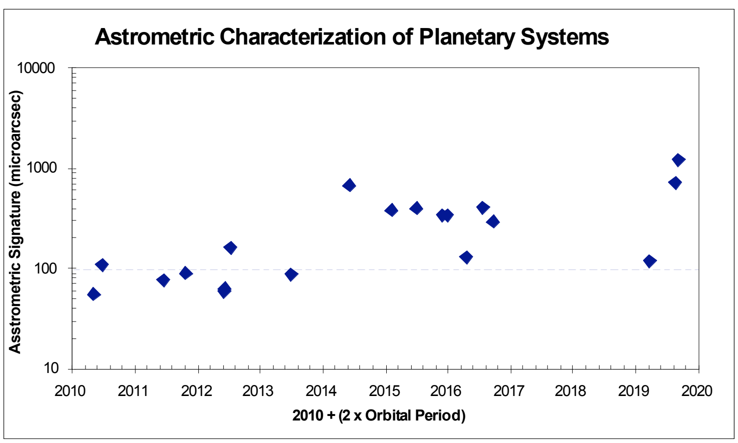


Figure 7. A sample of known exoplanets whose mass and inclination could be measured with the ASTRA-astrometry mode of the Keck Interferometer. An astrometric accuracy of 50 μ-arcsec will allow the interferometer to measure all of the targets in this plot. The targets are plotted in time versus the start of observations assuming that observations are needed over two times their period.

2. Science Enabled by Precision Optical and Near IR Spectroscopy

The development of the field of **exoplanet studies** has been truly explosive since the announcement of the first planet orbiting another star (51Peg). As of now, more than 320 exoplanets are known orbiting more than 275 stars. The vast majority of these planets have been discovered via the radial velocity technique, and Keck/HIRES has led the way.

Currently, the known planets range in mass from super-Jupiters to sub-Neptunes down to 10-15 Earth masses. The quest now has turned toward finding and characterizing earth-like planets in the "habitable zone." Because the radial velocity semi-amplitude is proportional to m_{planet}/m_{star}, there is great advantage to searching around lower mass primary stars in order to find the earth-mass planets. For example, a 0.1 M_{sun} late-M dwarf with an earth mass planet orbiting within its (luminosity dependent) habitable zone at 0.02 AU would exhibit 2 m/s reflex motion. Although this is within the velocity precision of the best of the optical high dispersion spectrographs employed for planet searches, the challenge is sensitivity. For stars later than M5 dwarfs, near IR spectrometers will be more efficient than optical spectrometers such as HIRES. Indeed, planets and planetary systems have been discovered around several M stars and the solar neighborhood is dominated by M stars, which outnumber AFGK stars within 10 pc by roughly 3:1 (and more at closer distances). A near IR instrument on Keck could survey over 1000 M dwarfs.

3. Science Enabled by High Sensitivity, 2D Faint-Object Spectroscopy

KCWI is designed to provide visible band, integral field spectroscopy (IFS) to Keck, with moderate to high spectral resolution, various field of view and image resolution formats, high efficiency, and excellent sky-subtraction. IFS at Keck will benefit from the excellent seeing, low sky background, large aperture, and high KCWI throughput, providing a world-leading capability that will enable the following science:

Galaxy-IGM-Circum-Galactic Medium Co-evolution. One of the forefront topics today is the connection between galaxies and the gas in their dark matter halos (Circum-Galactic Medium [CGM]) as well as with the IGM gas in the cosmic web. KCWI is optimal for detecting low surface brightness emission from redshifted Lya, OVI, and CIV over the redshift range 2<z<6. For example, the Lya halos around Lyman Break Galaxies trace gas in dark matter halos which may be fueling star formation and galaxy formation, or represent material that has been energized by galactic superwinds (Figure 8). Separating the different emission components, isolating the excitation mechanism for resonance line emission, dissecting Lya radiative transfer, and separating foreground objects and companions require 2D spectral imaging with excellent sky subtraction, high sensitivity, good imaging resolution, and moderate (R~3000) spectral resolution.

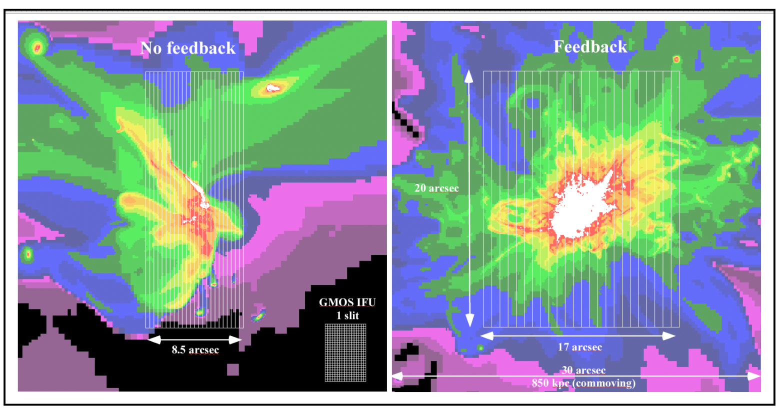


Figure 8. Simulation of Lya (z~2.5) emission from CGM performed by Greg Bryan, with KCWI field of view. Color scale is logarithmic, with medium green corresponding to the 5 sigma sensitivity limit in 5 x 5 arcsec^2 emission regions for KCWI after 8 hours of integration (orange is 10 times higher intensity, blue ten times lower). LEFT: CGM with no feedback, narrow/fine IFU. RIGHT: CGM with feedback, medium field of view IFU (see Table 1).

High z galaxy environments / assembly. High redshift galaxies are likely to lie in complex, multi-component systems with fainter companions and extended stellar and gaseous features. KCWI will detect these fainter companions and measure relative velocities and other properties. 2D coverage permits summing light from extended components and producing the highest possible SNR spectra.

AGN/QSO hosts/ionization/Circum-QSO Medium/QSO absorption lines. Prior to and shortly after QSOs are born, the Circum-QSO medium (CQM) may be a fair representation of the typical QSO environment. In particular, the CQM, which will be illuminated by the QSO providing high SNR emission maps of the CGM around galaxies at 2<z<6. Coupled with an occulting spot, it should be possible to explore QSO host galaxy, host environment, and intervening absorber galaxy properties.

Metagalactic ionizing background can be measured in principle at high redshift using Lya fluorescence, and at low redshift using Ha or Hb emission. Reaching the very low surface brightness required, and separating out other mechanisms for producing the emission is best accomplished with 2D spectral mapping designed to probe emission strengths <0.1-1% of sky.

Reionization HII Regions. Models predict that during the epoch of reionization (z>6) growing HII regions should be detectable by extremely faint and highly extended (many arcmin) Lya emission, detectable by KCWI to a redshift of z~7.2. This is a pioneering but challenging observation that cannot be performed by any other facility.

Intracluster Light has been detected in many nearby clusters, and is believed produced by stars stripped from their galaxies as the groups and cluster assemble, as well as by stars formed during the interactions in tidal streams. KCWI would provide kinematic maps and line-index diagnostics that could provide stellar age and metallicity information crucial to unraveling these stellar relics.

Strong lens systems are complex, 2D systems that could be analyzed in detail using KCWI spectral images, which would provide information about the lensing galaxy (redshift, velocity dispersion, mass, stellar populations) and lensed galaxy (stellar populations, star formation rate, age, metallicity, etc.).

Galaxy stellar kinematics and populations. KCWI could extend kinematic and stellar population measurements to the unexplored low surface brightness regions in the outskirts of galaxies, probing relic structures with long dynamical times and memories of their assembly history, and probing kinematics in dark matter dominated dwarfs.

4. Science Enabled by New Capabilities in Wide-Field Spectroscopy

Keck Observatory is exploring new initiatives to expand its wide-field spectroscopic capabilities at both low and high resolution with these science areas in mind:

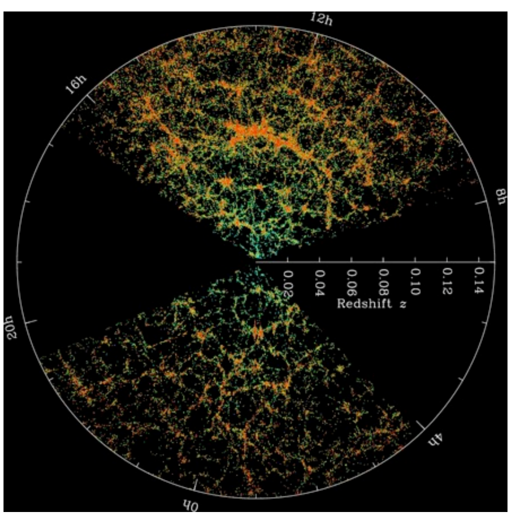
Moderate-to-High Resolution, Highly Multiplexed Spectroscopy

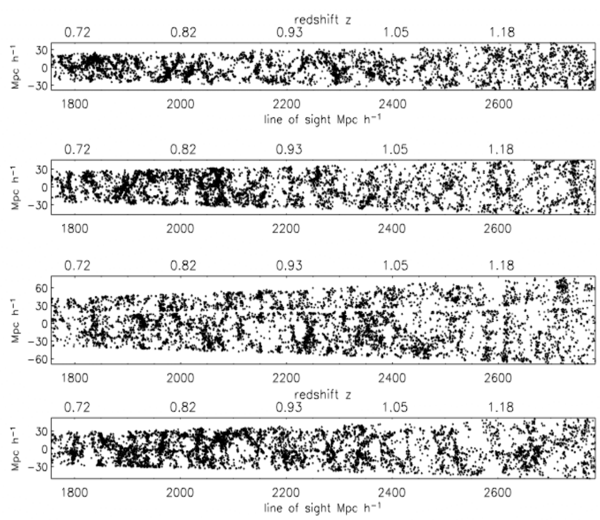
Local Group dwarf Spheroidals: Surveys of the kinematics and chemical abundances of low luminosity dwarf spheroidal satellites address critical questions on the nature of dark matter and the nature of early galaxy formation: Are the recently discovered low luminosity dwarfs the last remnants of the primordial population that perhaps formed prior to reionization? Is their detailed chemistry different from the field halo and the more luminous dwarfs? Many new systems are certain to be discovered (via PANSTARRS, LSST), and a capability is currently missing at Keck to undertake a major program of spectroscopy on large numbers of stars per galaxy. **Galactic bulge:** High-resolution spectra of bulge dwarfs, which are faint (R~18-19) and crowded, could be obtained for ~50 such stars per field in multiple fields with ~1/20 sq. degree FOV. These stars may be selected to have proper motion measurements from *HST*, making it possible to explore correlations between kinematics and composition. It should even be possible to select for stars that have candidate transiting planets offering the possibility of measuring planetary masses and properties across a wide swath of the Galaxy.

Extragalactic globular clusters: Moderate-to-high resolution multiplexing spectroscopy allows the measurement of integrated light chemical abundances for globular clusters in galaxies ranging from M31 to the brightest objects in the Virgo Cluster. In the 10-m telescope era, metal-poor globular clusters are essentially the only indicators of the chemical abundances of stellar halos beyond the Local Group. Data of lower signal-to-noise than required for abundance studies can yield velocity dispersions and thence mass-to-light ratios for large samples of extragalactic globular clusters. These data also allow the exploration of the relationship between dwarf nuclei and ultra-compact dwarf galaxies. Globular clusters can be efficient tracers of halo substructure and cold streams, especially when both kinematical and abundance information are taken into account. A straw-man spectrograph covering ~ 0.1 sq. deg could obtain radial velocities for 1500--2000 globular clusters in M87 in a few nights, allowing an extraordinarily accurate profile of the halo mass and anisotropy, independent of other data. For most galaxies close enough for GC system studies, the ideal FOV is more like ~1/20 sq. degree.

Ultra-Wide-Field Spectroscopy

The formation and evolution of galaxies at z~1: As pioneering surveys of nearby galaxies demonstrated, redshifts remove the effects of projection, reveal the cosmic web, and allow conversion of observed fluxes and sizes to physical rest-frame quantities. Whereas the local galaxy population (z<0.1) is now well surveyed (SDSS, 2dF), the leading projects at z~1 (e.g. Keck/DEEP2) remain limited by cosmic variance because of their small survey volumes. Because galaxy properties correlate with large-scale structure, one must map much wider areas of the sky at z=1 and beyond to construct a coherent picture of galaxy evolution, to understand the interplay of star formation, stellar mass build-up, accretion through mergers, feedback from stars and AGN, and the effects of environment over cosmic time. Such efforts benefit from a low-dispersion, highly efficient spectrograph multiplexed for 1000 targets across $\geq 0.1 deg^2$.





5.

Science Enabled by a Flexible Observatory

Keck Observatory, by virtue of its user community, aperture size, and instrument suite has been a leader in **time-domain astrophysics** (TDA) discoveries, with, for example, the 1) first inference of dark energy with photometry and spectroscopy of supernovae, 2) measurement of the orbits of stars around Sgr A*, providing the location and mass of the black hole at the center of the Galaxy, 3) leading in the discovery of exoplanets, 4) discovery of Dysomnia, a moon with common proper motion with Eris, the largest dwarf planet, 5) discovery of the cosmological nature of gamma-ray bursts, 6) discovery of the largest volcanic eruption in the Solar System on Io and the first spectrum of an Io eruption. With other 8–10m class telescopes on-line, many of which are queue-scheduled and some with rapid instrument switching capability, it is clear that Keck is facing increased competition and is in serious danger of ceding important scientific ground unless its time-domain capabilities are improved. For instance, Next Generation Imaging Surveys (NGISs), such as Pan-STARRS and LSST, will soon routinely produce hundreds to thousands of transients per night. The phase space for new discoveries is enormous and Keck must position itself to capitalize on the "needles in a haystack." In addition, there are several representative TDA science areas of broad interest to our community:

Black Hole Tidal Disruption Events: These should be found by NGISs by the dozens in the next few years, offering a new window on black hole growth in the distant universe. Keck observations could provide crucial spectroscopic confirmation, redshifts, and monitoring of emission-line diagnostics and variability over timescales of weeks to months.

Progenitors of Supernovae: High-resolution imaging of SN progenitor sites enables the correct selection of the progenitor from among the stars in the pre-explosion SN images. After decades of effort, only seven SN progenitors have so far been detected. The use of Keck LGS-AO represents a promising direction for such studies.

Gamma-Ray Bursts as Probes: As bright lighthouses, GRB afterglows for hours can outshine the brightest quasars in the sky. Systematic programs could use GRBs to understand the nature of damped Lya systems, ISM and molecular clouds in distant galaxies, and non-continuum features extragalactic extinction curves. GRB afterglows are also providing probes of the early universe (into the Epoch of Reionization), before the assembly of supermassive black holes capable of producing bright quasars. In this respect, rapid access to low- to moderate-resolution IR spectroscopic capabilities with Keck must be cultivated.

Technical Overview

1. New Capabilities in Very High Angular Resolution Astronomy

NGAO

The following key new capabilities are being developed for the NGAO system: Near diffraction-limited observations in the near-IR (K-Strehl ~80%); AO correction at red wavelengths (0.65-1.0 μm); Increased sky coverage; Improved angular resolution, sensitivity and contrast; Improved photometric and astrometric accuracy, Imaging and integral field spectroscopy.

Design Overview

The NGAO technical approach is shown schematically in Figure . The requirement of high Strehl over a narrow field is achieved using laser tomography (to correct for focal anisoplanatism; i.e., the "cone" effect) with an on-axis LGS and three uniformly spaced LGS on a 10" radius (as illustrated in Figure), a narrow field relay with a deformable mirror having 64 actuators across the telescope pupil and careful control of all wavefront errors especially tilt errors. High sky coverage is achieved by sharpening the three stars used to provide tip-tilt information with their own LGS AO systems including a movable LGS (shown in Figure 10) and a MEMS DM with 32 actuators across the telescope pupil (i.e., the low order wavefront sensors shown in Figure 9). High sensitivity at thermal wavelengths requires low emissivity which is achieved by cooling the science path optics (e.g., the cooled enclosure in Figure 9).

The initial NGAO science instrument will provide both imaging and integral field spectroscopy from 0.65 or 0.8 to 2.4 μm. At the short wavelength cut-off the instrument will allow observation of the Ca II triplet (~850 nm) with a goal of reaching Hα (~656 nm). The imager will have a 35" x 35" field of view and will provide at least 2 pixel sampling of diffraction limited z-band images (8.5 milli-arcsec/pixel) with low internal wavefront error, and a coronagraph.

An integral field spectrograph (IFS) is ideally suited to take advantage of the image quality offered by AO because of its ability to provide spatially resolved spectroscopy of diffraction limited images. IFS data can provide information essential for deconvolution of the PSF and offers a comprehensive tool for determining kinematics, mass distributions and velocity dispersions.

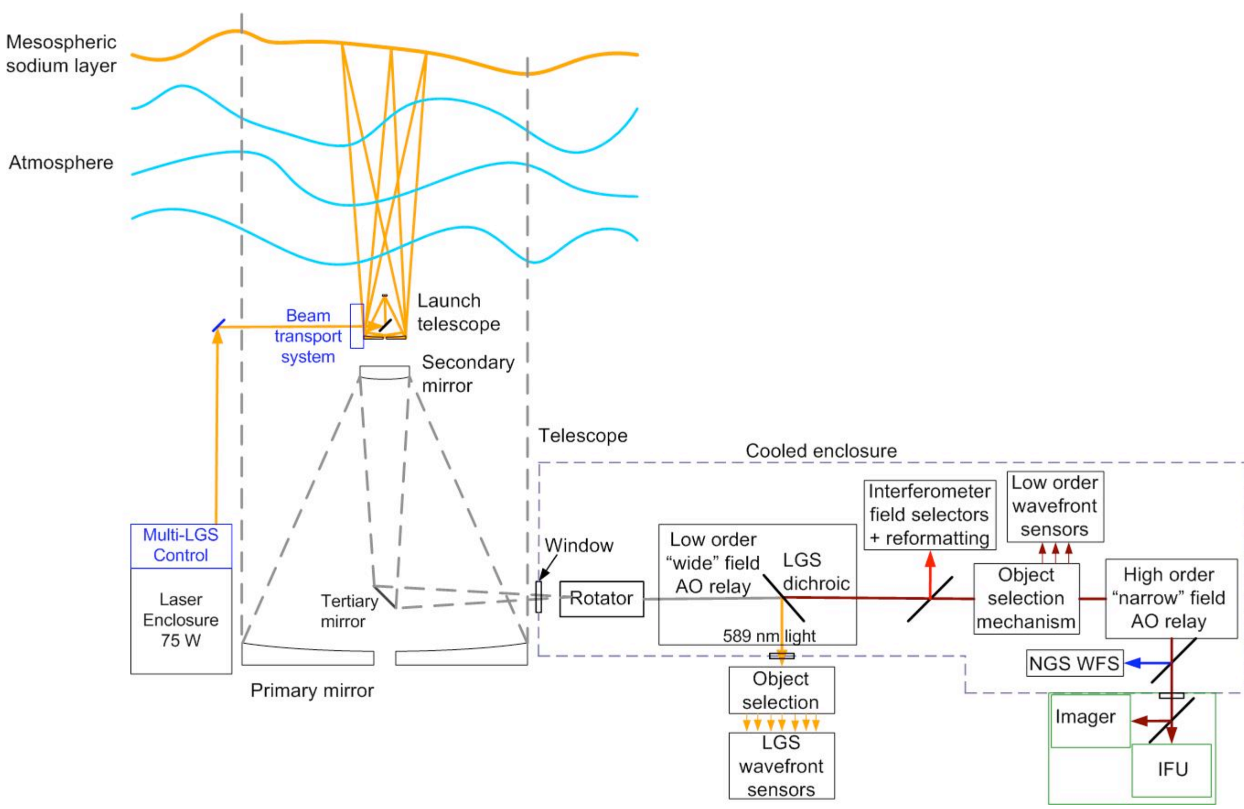


Figure 9. Schematic of the NGAO concept

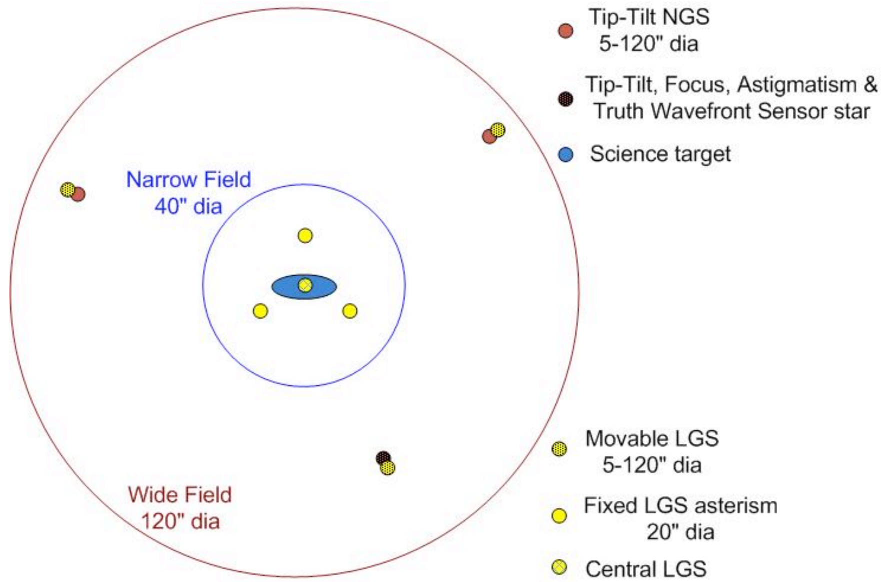


Figure 10. Schematic of the NGAO LGS asterism

The NGAO IFS will be an advanced design based on lessons learned in the development of the first generation of AO-corrected near-IR IFS instruments for large telescopes and an improved understanding of the science requirements gained through observations with the currently available instruments. The IFS will be optimized to take advantage of the lower backgrounds, higher throughput, higher Strehl, and extended wavelength coverage possible with NGAO. The IFS will have higher sensitivity than current near-IR IFS instruments and will provide a 4" x 4" FOV with 0.050 to 0.075" spatial sampling optimized to match the ensquared energy in the NGAO science field. The IFS will also provide spatial sampling matched to the diffraction limit in the K-band with a 2" x 2" FOV, and a fine sampling scale (~0.010") for the short wavelengths.

The real-time control system architecture for NGAO uses the massively parallel processing approach shown in Figure 11 along with an iterative Fourier domain preconditioned back projection tomography algorithm.

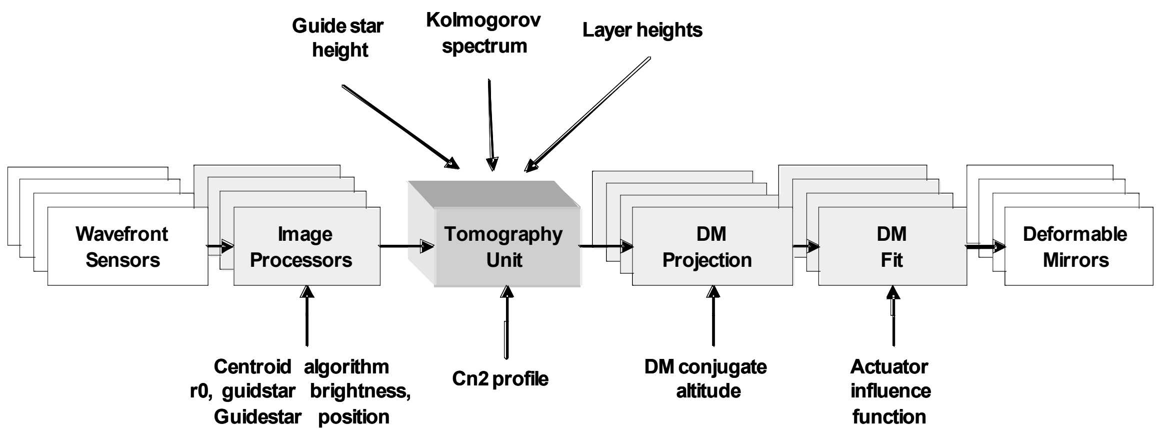


Figure 11. NGAO's real-time control parallel processing architecture

Performance Overview

A detailed wavefront error budget has been developed for NGAO based on a combination of simulations, anchors to the existing Keck AO system performance and measured atmospheric and sodium conditions. The performance of the NGAO design has been evaluated for each of the key science cases at the wavelengths of most interest to each science case. Figure 12 (bottom left) shows the predicted Strehl ratio for the exoplanet science case at H-band and 10º galactic latitude, as a function of sky coverage. Figure 12 (top right) is a similar plot for the AGN science case at z-band and a galactic latitude of 30º. For this science case the energy in a particular IFS diameter is the performance parameter of interest. The tip-tilt error is shown separately in both of these figures since the impact of increasing tip-tilt error is to increase the diameter of the core of the PSF without decreasing the amount of energy in this core. Overall NGAO is predicted to have excellent sky coverage due to the use of multiple AO-corrected tip-tilt stars.

The performance versus off-axis distance for the Galactic Center science case is shown in Figure 13. The Strehl is the important parameter for reducing source confusion and thereby improving the accuracy of astrometric imaging observations. The ensquared energy is important for the corresponding IFS radial velocity measurements. In this application the IFS will have a maximum size of 2" radius while the science imaging requirement is a radius of 5". If more uniform Strehl performance was required this could be accomplished by optimizing the performance for a different radius at the expense of the on-axis performance.

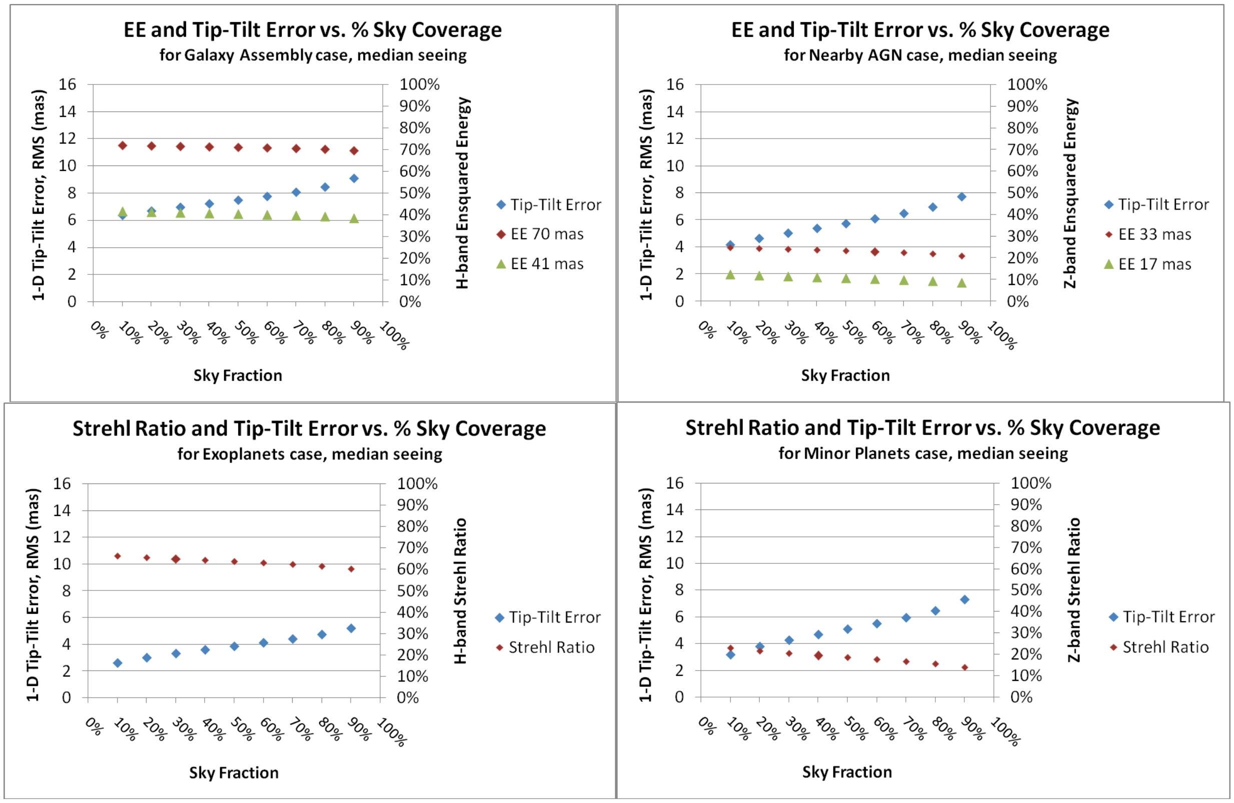


Figure 12. Key performance parameter plots versus sky coverage for four key science cases. The top two plots show ensquared energy (right axis), within the dimension specified in each plot's legend, for the galaxy assembly in H-band and nearby AGN in z-band science cases. The lower two plots show Strehl ratio (right axis) for the exoplanet in H-band and minor planets in z-band science cases. The rms tip-tilt error is shown versus the left axis in all four plots; the tip-tilt errors are relatively small in comparison to the ensquared energy areas.

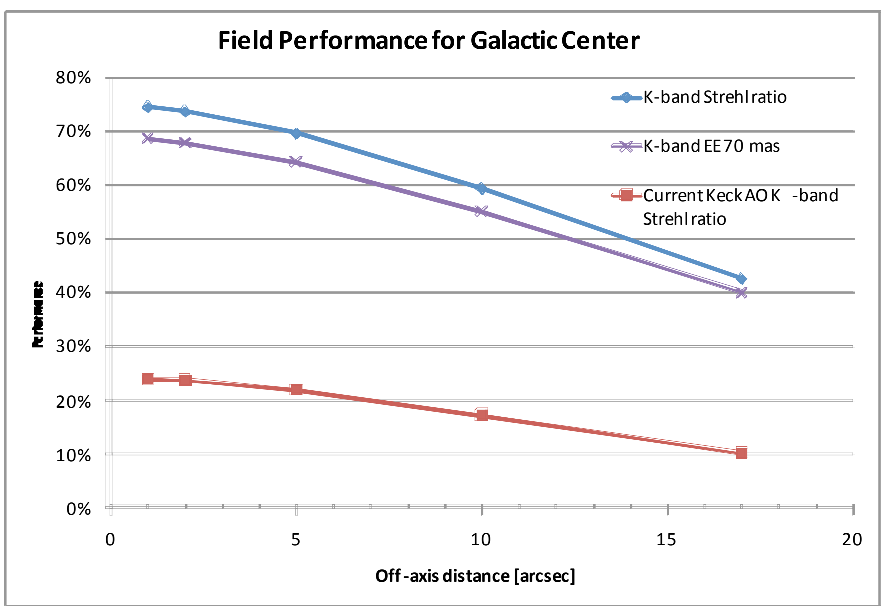


Figure 13. NGAO Strehl ratio and ensquared energy (in a 70x70 mas area) for the Galactic Center science. The maximum off-axis distance is 2" for integral field spectroscopy and 5" for imaging of the Galactic Center.

A summary of the predicted NGAO performance for the key science cases is shown in Table 1. The rough comparison between current Keck AO performance and NGAO shown in Figure 14 illustrates the dramatic science improvement that will be provided by NGAO.

Table 1 Predicted performance for the NGAO key science cases

Science Case	High order wavefront error (nm)	Tip-Tilt error (mas)	Effective wavefront error (nm)	Science Performance		
				Science Band	Strehl Ratio	Ensquared Energy
Gal Center imaging (1" off-axis)	188	1.4	189	K	75%	
Exoplanets	162	3.3	171	H	65%	
Minor Planets	162	4.3	177	z	20%	
Galaxy Assembly	162	7	204	K		71% in 70 mas
Nearby AGN	162	5	182	z		24% in 34 mas

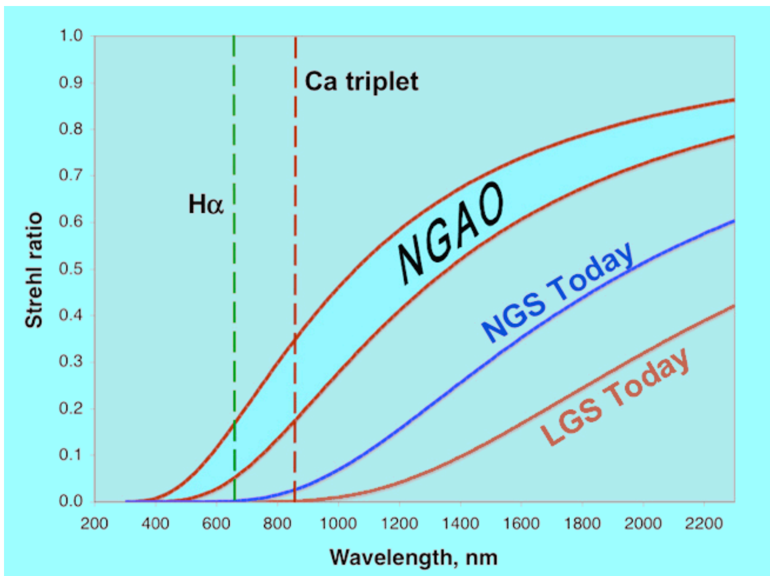


Figure 14. NGAO versus current Keck II NGS and LGS AO performance (for the case when a bright natural guide star is available for NGS AO or for tip-tilt correction with LGS AO).

NGAO's Capabilities versus JWST and GSMT

A comparison of the NGAO capabilities to those of JWST and TMT has been performed. JWST's sensitivity is ~200 times higher than NGAO at K-band, but NGAO offers higher sensitivity than JWST for imaging at or bluer than J-band (by ~6 times at J) and for spectroscopy between the OH-lines at H-band or bluer. NGAO offers higher spatial resolution for both imaging and spectroscopy (from 0.65 to 2.4 μm) due to a larger telescope and higher spatial sampling (0.009"/pixel versus 0.032"/pixel for JWST).

NGAO will have already made a significant scientific contribution prior to the start of science operations with TMT or GMT. NGAO will offer similar Strehls as TMT's first light AO system but with lower spatial resolution (at the same wavelength) and similar spatial resolution for IFS science but with lower sensitivity. As TMT arrives on the scene NGAO could move to new areas such as shorter wavelengths or multiple object spectroscopy. Even in the GSMT era NGAO will remain an ideal platform for long term precision synoptic science from astrometric and radial velocity measurements of the Galactic Center to weather monitoring of solar system planets and moons.

Technology Drivers

In order to achieve the required science performance NGAO must offer improved performance in a number of areas that have not yet been demonstrated. The NGAO design process has therefore been one of finding solutions to the reduction of numerous error terms while simultaneously finding ways to minimize risk and cost.

Laser Guide Star Tomography

NGAO will use four LGS beacons (Figure 10) to perform tomography of the atmosphere in a narrow volume around the science field. The primary purpose of tomography is to reduce focal anisoplanatism (i.e., the cone effect); the single largest wavefront error term for the current Keck II LGS AO system. Laser tomography has not yet been demonstrated on the sky despite the fact that it is planned as a key part of future AO systems on existing telescopes as well as future extremely large telescopes. We have compared multiple tomography simulation codes, followed the results of NGS tomography demonstrations and performed experiments at the UCSC Laboratory for AO to better quantify the tomography error.

The data from multiple wavefront sensors are combined to determine the wavefront error as a function of altitude and direction. In the NGAO system this information will be used to provide the optimal on-axis correction. This information could alternatively be used to optimize the performance at any given field point within the tomographic volume. We also intend to use the tomographic information in support of providing PSF calibration data versus field position.

Laser tomography requires the availability of high return sodium wavelength lasers. Toward this end WMKO was a participant in a consortium also consisting of Gemini Observatory, the Air Force Phillips Lab and the Center for Adaptive Optics that resulted in the Starfire Optical Range (SOR) laser and the lasers that Lockheed Martin Coherent Technologies has or is producing for Gemini and WMKO. Despite these successes the availability of affordable and reliable commercial sodium wavelength lasers continues to be a major issue for the astronomical community. We are now collaborating with ESO, GMT, TMT and AURA to fund two companies to develop preliminary designs for commercial lasers that have been specified to meet our joint needs. The two companies are FASORtronics who are commercializing the SOR laser approach and TOPTICA who are developing a fiber Raman amplifier based laser system similar to the approach recently demonstrated by ESO in the lab. Based on the preliminary design results, due by the end of 2009, ESO intends to select one of these vendors to provide four 25W lasers for their planned 4LGS facility. WMKO would need three of these lasers for NGAO and TMT and GMT would each need ~6 of these lasers. These preliminary designs will also be exploring some new approaches including back-pumping of the sodium atoms which could potentially significantly improve the coupling efficiency to the sodium atoms and hence the return per Watt.

Near-IR Low Order Wavefront Sensing

The NGAO low order wavefront sensors (LOWFS) are a key element in achieving high Strehl with high sky coverage. Two of these LOWFS just provide tip and tilt based on measurements from natural guide stars in the 120" diameter field. A third LOWFS also measures focus and astigmatism. Three tip-tilt measurements are necessary to determine low order modes which the LGS wavefront sensors cannot measure. The use of AO-sharpened tip-tilt stars has not been demonstrated on the sky to date. A number of challenging technologies need to be incorporated into these LOWFS to achieve the required performance. These include:

- Pickoff arms to accurately acquire and track the tip-tilt stars with respect to the science field.
- MEMS deformable mirrors to sharpen the image of the tip-tilt star based on the wavefront sensor data from the LGS pointed at the tip-tilt star.
- Near-infrared low order wavefront sensor cameras.

Science Measurement Accuracy

Astronomers are interested in such key performance issues as sensitivity, spatial resolution, spectral sensitivity, contrast, astrometric accuracy and photometric accuracy. AO developers have traditionally designed and assessed their system performance versus wavefront error (or encircled energy) and transmission/emissivity budgets. In order to move to another realm of science performance the AO developers now need to develop error budgets for, and improved understanding of, the other relevant performance parameters impacting science with AO.

One key parameter is the point spread function (PSF) of the images delivered by the AO system; this needs to be determined in the absence of a PSF star in the science data. The structure of this PSF and its dependence on time and field position strongly impacts the accuracy of astrometric or photometric measurements, the ability to detect faint sources next to bright sources and the ability to characterize the structure of astronomical objects. Improving the stability of the PSF and knowledge of the PSF versus time and field position will directly improve the science achievable with AO.

In the process of developing NGAO we have begun to develop additional error budgets, for such areas as companion sensitivity, astrometry and photometry, in order to determine their impact on the NGAO design. We have also begun the process of implementing PSF characterization tools with the existing Keck AO system, based on existing wavefront sensor data supplemented by atmospheric turbulence monitoring data, as a stepping stone to developing the more complex tools that will need to be implemented with NGAO's laser tomography system. PSF characterization tools have not yet been implemented anywhere for LGS AO science or for NGS AO with Shack-Hartmann wavefront sensors.

Keck Interferometer ASTRA Phase Referencing and Astrometry

The technical steps in the development of the Keck Interferometer for phase referencing and astrometry is shown conceptually in Figure 15. The existing Keck Interferometer provides a powerful operational facility on which to build the new science capabilities. The three observing modes are described in the following bullets:

- **Self phase referencing** has been scientifically demonstrated and is operational. This mode provides R~1800 spectral resolution of science targets currently as faint as K~7. In self phase referencing, like adaptive optics (AO), some of the light from the science object is used to measure and control the wavefront (in this case the phase or piston between the two telescopes). A beam splitter is used to divide the science objects light and to send the light through separate interferometer delay lines to two fringe tracker cameras. The science integration time on one of these delay lines and cameras can be set to ~ 1 sec versus the 200 Hz update rate required for fringe tracking.
- **Dual field phase referencing** does the same as self phase referencing but using two separate targets (or fields), one for science and one for phase referencing, separated by up

to 30" in order to increase the limiting magnitude of the interferometer from K~10 to K~15 science targets. Since much more of the path is now non-common path additional metrology systems are required for both phase and angle (i.e., tip-tilt) tracking. In order to not be limited by the limiting magnitude of the AO systems it is also necessary to have laser guide star (LGS) AO systems on both telescopes (the Keck II LGS AO system has been operational since 2004 and the Keck I LGS AO system will be operational in 2010).

- **The astrometry measurement** is shown schematically on the right side of Figure 15. A differential phase measurement (Δ) between the two targets is turned into a measurement of the angular separation $\alpha = \Delta/B$ where B is the baseline between the two telescopes. Another level of metrology must be added along with systems to accurately measure the stability of the baseline between the two telescopes in order to achieve the required 30 μarcsec accuracy. This mode is planned to be ready for science observations in 2010.

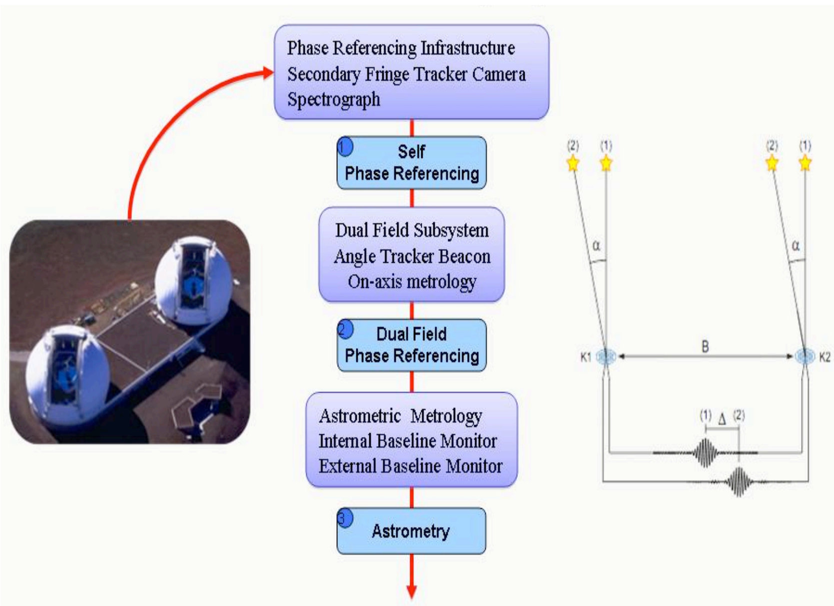


Figure 15. Development of the Keck Interferometer (KI) for phase referencing and astrometric science. The text boxes list the major components required to be added to move from the existing KI (left image) to self phase referencing, then to dual field phase referencing and finally to astrometry. The schematic at right shows how a phase difference measurement (Δ) is used to obtain the angular separation (α) between two stars based on the baseline distance (B) between the two Keck telescopes.

2. Precision Optical and Near IR Spectroscopy

As discussed above, mid-M dwarf stellar targets (~0.2-0.5 M_{sun}) observed in the near-infrared appear to be the sweet spot for the first detection of earth-mass planets. Innovative instruments on Keck will enable Keck to play a leading role in the search for earth-mass exoplanets orbiting low mass stars. One such example is an interferometric front-end instrument coupled to the Near Infrared Echelle Spectrometer (NIRES) currently in assembly. Such an instrument could achieve σ_v ~2-5 m/s for H=10 late-type stars in a 5 min integration on the Keck telescope. There are more than 1000 M dwarfs brighter than V=12, and more than 2000 currently known M dwarfs later than M4V. A prototype for such instrumentation is currently under development and testing at the Palomar Observatory (TEDI). If successful, Keck will consider its implementation (NEDI) in the upcoming decade.

To date, the radial velocity technique at optical passbands has been by far the most successful approach to discovering new planets. And although other approaches are producing spectacular new results, precision radial velocity studies, in particular those with precision to <1 m/sec, will continue to play a central role in extra-solar planet research for the foreseeable future. There are several opportunities for improving the Keck Observatory capabilities in this area:

- Build a new dedicated spectrometer optimized for precision Doppler measurements. A key improvement is to significantly increase the effective bandpass over which the measurements are made beyond the Iodine cell approach in HIRES.
- Build a fiber-based "scrambler" for the HIRES slit feed. The scrambler will ameliorate changes in pupil illumination due to imperfect centration of the star on the slit that is a limiting factor in velocity precision.
- Build a combination fiber scrambler and image slicer to either improve efficiency at the slit or to work with the same efficiency as now, but with higher spectral resolution.

3. KCWI -- High Sensitivity, 2D Imaging Faint-Object Spectroscopy

KCWI is an image slicer integral field spectrograph. The KCWI instrument configurations are detailed in Table 1 below. The instrument combines a reflective image slice (24 slices), several folding flats, a simple collimator, a dichroic that forms the two optimized optical channels (red and blue), and existing blue camera, a high QE *e2v* 4k x 4k CCD optimized for blue QE for the blue channel and a new camera and deep depletion CCD for the red channel. Source/background shift-and-nod provides the required sensitivity and 10^3-10^4:1 background rejection to unambiguously detect low surface brightness emission against a complex sky spectrum. The spectrograph obtains a moderate to high spectral resolution, using high efficiency Volume Phase Holographic gratings.

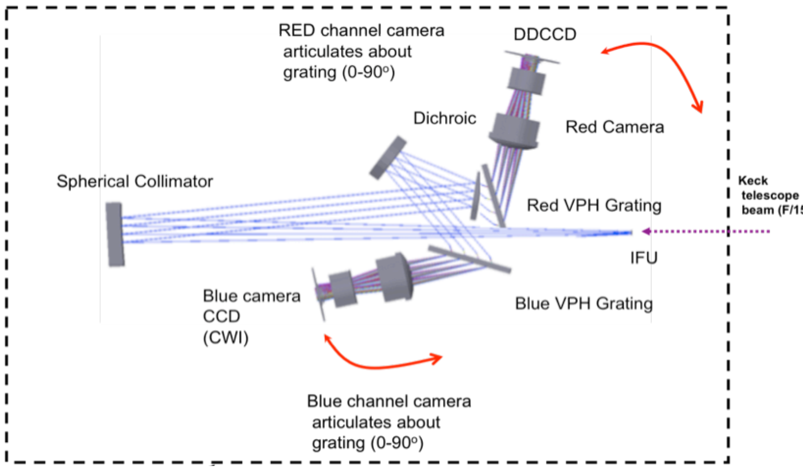


Figure 16. KCWI optical layout

Table 1 –KCWI Instrument Configurations

		Spatial Resolution			
		⊥ Dispersion	‖ Dispersion (Slicer-width) Direction		
			Fine	Medium	Coarse
		0.3″	0.35″	0.7″	1.4″
		FOV 20″x	8.4″	16.8″	34″
Spectral Resolution					
High	Instantaneous $\Delta\lambda/\lambda$	300Å /4000Å	R~20,000	R~10,000	R~5000
Medium	Instantaneous $\Delta\lambda/\lambda$	1000Å /4500Å	R~8400	R~4200	R~2100
Low	Instantaneous $\Delta\lambda/\lambda$	2500Å /5000Å	R~3600	R~1800	R~900

KCWI is designed to provide a wide range of capabilities, with emphasis on spatial sampling and spectral coverage. Spectral resolution, slicer width (image resolution in spectral direction) and bandpass are determined by the following simple relationship: $R(\Delta\lambda/\lambda)\theta=500$, where R is the spectral resolution ($R=\lambda/\delta\lambda$), $\Delta\lambda/\lambda$ is the fractional instantaneous wavelength coverage in one channel, and θ is the slicer width in arcseconds (spaxel size in dispersion direction). The optical layout is shown in Figure 16. KCWI will provide 3 image slicer formats swapped into place in less than a minute. The multiple slicers would be designed to feed a fixed pupil mirror array, so that the resulting virtual slit is identical in the three cases except for slit width. KCWI will use Volume Phase Holographic (VPH) gratings, which provide very high efficiency when operated near the Bragg condition. For the higher dispersion/resolution gratings, the bandpass is modest but sufficient to cover line combinations such as Hβ/[OIII] or Hα/[NII]/[SII]. The camera and grating are mounted on a rotating articulation unit that provides an arbitrary incidence angle to the grating and exit angle to the camera/detector. Full optical band coverage (3500 Å – 10,000 Å) would require 3 gratings on the blue side and three on the red side, assuming two simultaneous channels. Instrument throughput will exceed 25%.

The principle technical developments are the large, high dispersion VPH gratings required for the highest resolution modes. The finer image slicer pushes the limits of slicer fabrication. KCWI will probably provide flexure compensation or an image derotator. Deep Depletion CCDs are still considered developmental.

4. New Capabilities in Wide-Field Spectroscopy

Keck observatory is considering several paths toward multi-object, moderate-to-high resolution optical spectroscopy over wide fields, a capability that it currently cedes to many of the other 8 to 10m class telescopes (e.g. FLAMES, GIRAFFE/VLT; Hectoechelle/MMT). With one exception (MOE on Magellan), these are all wide-field, fiber-fed instruments. A high throughput multi-object echelle spectrograph on Keck would potentially enjoy a 1 mag or greater gain on these instruments, making it a unique facility.
The science described above demands a spectral resolution of at least ~20000, with a slit size set such that at median seeing at Keck most of the light from a point source goes through the slit.
It is critical to achieve a multiplexing of at least a factor of 20 while maintaining substantial wavelength coverage per object for abundance measurements on more chemical species or greater redshift coverage. Finally, a throughput exceeding 15% is needed to maintain an advantage over existing instrumentation at other observatories.

One approach to accomplish this is by **modifying the Low Resolution Imaging Spectrograph (LRIS),** an existing optical spectrograph at Keck which already has a reasonably large field with multi-object capability. This will provide a cost-effective way to rapidly bring online the desired new capability. The maximum spectral resolution of LRIS today is ~4500 for a 1200 g/mm grating used with a 0.7 arcsec wide slit. Reducing the slit significantly from this is not feasible owing to the severe light loss it would incur. Harland Epps has identified an interesting configuration of dispersive elements which can increase the spectral dispersion without narrowing the slit nor increasing the beam size. We believe that Epps's new optical configuration can be implemented on the red side of LRIS, which is a double spectrograph with a red and blue side. The red side has recently been upgraded with the best available CCD detectors having very low readout noise. The capability of obtaining multi-object high resolution spectroscopy could thus be added to the suite of observing modes available for a cost of less than ~1 million dollars and could be completed within a year.

We have also begun exploring designs for a new facility instrument that would offer wide-field, multi-object spectroscopy at R~20000. Considerable effort has been expended by a team led by Rebecca Bernstein on the design of a moderate resolution multi-object instrument (MOBIE) for the TMT. We would also explore whether this concept can reach the desired spectral resolution if scaled back for a 10-m telescope and how the cost would scale.

In terms of the wide-field (>0.1 sq. deg.), low-dispersion instrumentation that would be ideal for galaxy and radial velocity surveys, Keck is challenged by its f/15 secondary and the difficulty of locating instrumentation at the prime focus. Members of the GTC (a Keck clone) community are currently pursuing designs for a fiber-fed instrument at the Cassegrain focus. Keck may leverage these efforts to initiate its own development in the next decade. WFMOS is a planned robotically-controlled multi-fiber spectrograph designed to exploit the unique 1.5 degree prime focus of the Subaru 8.2 meter telescope atop Mauna Kea. Up to 3200 fibers to be reconfigured in only 40 seconds, thereby allowing spectroscopy of 100,000 galaxies per clear night. If WFMOS has a future on Subaru, it may be appropriate to access this capability with Keck/Subaru time trades. If not, Keck might wish to explore avenues for accessing a federal/private funding package to pursue a cost-effective ultra-wide field capability on Keck.

5. Enhancing Capabilities in Infrared Spectroscopy

The WMKO Near InfraRed Echelle Spectrograph (NIRSPEC) was commissioned in April 1999. NIRPSEC offers both a low (R ~2,000) resolution mode and a cross-dispersed Echelle mode (R ~25,000) over the wavelength range of 0.96 to 5.5 μm. NIRSPEC has provided workhorse service, receiving approximately 100 observing nights per year. The continued development of infrared focal plane arrays offers the opportunity to upgrade NIRSPEC, an activity that would be responsive to requests from our observing community to improve the performance of the instrument in areas such as detector dark current and read noise, an improvement of particular interest for Echelle mode observations in the J, H, and K bands. Requests have also been made for improvements in spectral coverage in the K, L, and M bands, and a higher resolution mode, for example R ~60,000.

The most straightforward upgrade to NIRSPEC is to replace its current 1024 x 1024 pixel InSb science array with a 2048 x 2048 pixel 5 μm cut-off H2RG (Teledyne Imaging Sensors Hawaii-2RG). The improvements possible in dark current and read noise are significant. The dark current of the H2RG is a factor of 70 times lower than the InSb array. Using Fowler sampling the H2RG has been shown to provide read noise of 5 e^- rms compared to the 25 to 35 e^- rms obtained from the InSb detector with 16 Fowler samples. The H2RG also offers a higher charge storage capacity and improved quantum efficiency, 80% is routinely demonstrated from 1 to 5μm. Using the existing camera optics the smaller pixel scale of the H2RG would increase the spectral sampling from 3 pixels (0.43" slit width) to 4.5 pixels but would not provide any additional spectral coverage. However, this improved sampling may be an asset to improving the precision of radial velocity measurements.

A second upgrade that would provide a significant benefit to observing efficiency would be to upgrade the instrument's slit viewing camera to a 5 μm cut-off 1024 x 1024 H1RG. This would improve the sensitivity of the slit viewing camera for target centering and for slit guiding. The slit viewing camera optics would also need to be redesigned as the present refractive optical design is optimized for achromatic performance from 1 to 2.5 μm and is unlikely to provide satisfactory performance at longer wavelengths. Both detectors would be controlled using the Teledyne SIDECAR ASIC to provide a high performance readout system to replace the current obsolete read out electronics which are a concern for continued spare parts and repair support.

Improving spectral coverage or providing increased spectral resolution in Echelle mode would require more extensive design changes, at a minimum the existing spectrograph camera optics (a three mirror anastigmat) would have to be replaced to take advantage of the area of the H2RG not illuminated by the existing camera. Higher resolution would require sacrificing the low resolution mode; an additional grating position is unlikely to be practical within the current constraints of the instrument's opto-mechanical layout. Both of these options would require more extensive design work to determine their feasibility.

6. Time Domain Astronomy

The W. M. Keck telescopes were not designed with time domain astronomy (TDA) explicitly in mind. With the growing interest and emphasis in TDA, the observatory is exploring new technical and institutional solutions to enhance TDA science at Keck.

Nights (or portions of a night) on the Keck telescopes are assigned 'classically' and the PI maintains full control over his/her assigned night. Although this approach to scheduling confers many benefits, it does create an impediment to efficient TDA observation, in comparison with queue scheduling models. Furthermore, current TDA policies are established individually by each partner and these do not allow for cross-institution observations. An example of the limitations this imposes to TDA science is as follows: if a TDA project were awarded by NASA for monitoring near-Earth asteroids with the NIRC2 camera, there is only a 0.7% probability that the observer could access NIRC2 on any given NASA night. With inter-institution cooperation, this would increase to 23%. Additional efficiency improvements may require further changes to Keck operations, including the possibility of some hybrid form of classical and queue scheduling under the direct control of the observer.

In tandem with advancing policy changes for TDA science, the observatory is exploring the possibility of making available on short notice, several instruments during the course of a night. Current practice is to guarantee availability of only the scheduled instruments on a given night (with some limited exceptions). It is feasible to expand this to make additional instruments available on timescales of ~15min. In some cases this is as simple as keeping instruments on standby. Other possible approaches being considered include fiber-fed instruments (though significant light loss may be a problem) and telescoping tertiary systems to redirect the light path. In the longer term, special purpose new systems containing multiple instruments could be constructed to allow rapid switch over in support of TDA science.

Keck has been a leader at developing efficient and fully featured remote control facilities to enable observation from sites distant from the telescopes. Indeed, 13% of observations are now done solely from sites at one of the partner institutions. Expanding this effort to support TDA science is a straightforward and natural outgrowth.

Appendices

Appendix 1. Keck Strategic Retreat Participants

Participant	Institution	Role
Mike Bolte	U.C. Santa Cruz	Director, UC Observatories
Aaron Barth	U.C. Irvine	WMKO community member, Extragalactic science
Jean Brodie	U.C. Santa Cruz	SSC Co-chair
Andrea Ghez	U.C. Los Angeles	WMKO community member, Galactic science
Garth Illingworth	U.C. Santa Cruz	WMKO community member, Extragalactic science, National community perspective
Jason X. Prochaska	U.C. Santa Cruz	SSC member
Alex Filippenko	U.C. Berkeley	SSC member
Jerry Nelson	U.C. Santa Cruz	SSC member
Mike Liu	U. Hawaii	SSC member
Alan Stockton	U. Hawaii	WMKO community member, Extragalactic science
Shri Kulkarni	Caltech	Director, Caltech Optical Observatories
Lynne Hillenbrand	Caltech	SSC Member
Chris Martin	Caltech	In-coming SSC Co-chair
Tom Soifer	Caltech	Out-going Caltech SSC Co-chair
Wal Sargent	Caltech	Former Caltech SSC Chair
George Djorgoviski	Caltech	Former Caltech SSC Chair
Keith Matthews	Caltech	MOSFIRE, NIRES, NIR instruments
Rachel Akeson	NASA/IPAC	SSC member
Tom Greene	NASA/Ames	SSC member
Zlatan Tsvetanov	NASA/HQ	NASA Keck Program Scientist
Chas Beichman	NASA/IPAC	Director, NASA Exoplanet Science Institute
Taft Armandroff	WMKO	Director
Hilton Lewis	WMKO	Deputy Director
Robert Goodrich	WMKO	Observer Support Lead
Peter Wizinowich	WMKO	Optical Systems Lead, NGAO Project Manager
Debbie Goodrich	WMKO	Development Lead

Appendix 2. Progress in Meeting 5 Year Goals of 2003 Strategic Plan

Development of a plan, and its initial implementation, for closed-loop control of the image quality delivered by the telescope to the instruments. The goal is to be limited only by the natural seeing at any time for non-AO instruments. Implement procedures for evaluating and monitoring image quality, and instrument throughput.	Autofocus on NIRSPEC has been implemented via MAGIQ. We plan to extend MAGIQ to other instruments (e.g., LRIS, MOSFIRE, & HIRES), which will yield continuous closed-loop focus control.
Integration of laser beacon for routine AO correction	Done
Improvements to AO interface and performance	Done
Implement atmospheric dispersion compensation for LRIS	Done
Upgrade CCD for LRIS-R	Done
Development of an interface and ICD for visitor instruments that can be brought to Keck to take advantage of unique science opportunities	Visitor port developed. NIRES is first instrument. A draft ICD is available for future instruments.
Near IR wide-field imaging/multi-object spectroscopic capabilities (MOSFIRE)	Underway; to be completed by end of 2010
Improved guiders/acquisition systems	MAGIQ is operational on NIRSPEC; work on MAGIQ for LRIS and MOSFIRE is underway.
Instrumentation to further exploit AO capability	OSIRIS and NIRSPAO are available.
Definition and initial development of next generation Keck AO system (KPAO, other?)	NGAO system design has been completed and preliminary design is underway.
Near-IR detector upgrades (NIRC2/NIRSPEC)	No progress to date
Over coated silvering of K2 primary, secondary and tertiary	No progress to date
Adoption and development of a new detector electronics design that will be standardized and capable of serving our needs (at both optical and IR wavelengths) for the next decade.	MOSFIRE is using an innovative detector electronics architecture that can be applied to future IR detector upgrades and future IR instruments.

Appendix 3. Science Opportunity/Recommended New Capability Matrix

	High Cost ←							→ Low Cost
	NGAO NIR imaging, Astrometry	NGAO IFS Near IR	NGAO optical	DEIMOS-x2, blue enhanced	Visible IFS	ASTRA	Efficiency Enhancements (coatings, IQ, time effic.)	Innov. Schedule
Solar system	✔	✔	✔				✔	✔
Exoplanets	✔	✔	✔			✔	✔	✔
Young stars, PPD, debris disks	✔	✔	✔			✔	✔	
Low mass stars	✔	✔				✔	✔	✔
Galactic Center	✔	✔				✔	✔	✔
MW and galactic archaeology				✔	✔		✔	
Young and globular clusters	✔	✔		✔	✔		✔	
Local group, Satellites	✔		✔	✔	✔		✔	
Gravitational Lenses	✔	✔	✔		✔		✔	
IR surveys	✔	✔					✔	
Transient Surveys				✔			✔	✔
Synoptic surveys	✔	✔	✔	✔			✔	
Galaxy evolution	✔	✔	✔	✔	✔		✔	
Reionization					✔		✔	
IGM				✔	✔		✔	
Cosmology				✔			✔	
Supernovae	✔			✔	✔		✔	✔
GRB	✔	✔		✔	✔		✔	✔
QSOs/AGN	✔	✔		✔	✔	✔	✔	✔

Appendix 4. Glossary of Terms and Acronyms

NGAO
ASTRA
GSMT
LSST
Spitzer
PanSTARRS
Kepler
WISE
NuStarr
GAIA
JWST
GSMT
TMT
ALMA
UKIDSS
VISTA
WFMOS
ELT/EELT
VLT
GTC
MMSS
WFMOS
TSIP
MRI
ATI
NIGS
MEMS
NIRES
VPH
PSF