W. M. KECK OBSERVATORY

The Next Generation Adaptive Optics System
at the
W. M. Keck Observatory

A Proposal for Design and Development
Executive Summary

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Final Version

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Abstract

The Keck telescopes are the world's largest optical and infrared telescopes. Because of their large apertures the Keck telescopes offer the highest potential sensitivity and angular resolution currently available. Unfortunately, without a means to overcome the performance limits imposed by the turbulence of the earth's atmosphere much of the superiority of the Keck telescopes would remain unrealized. Adaptive optics (AO) is now an established and fundamental technique for overcoming the performance limiting effects of atmospheric turbulence. The W. M. Keck Observatory has been among the leaders in the application of AO and the importance of achieving the full potential of the Keck telescopes is recognized in the Observatory's strategic plan which identifies leadership in high angular resolution astronomy as a key long-term goal.

At this time we face a number of challenges to our leadership in high angular resolution astronomy because of the aggressive development efforts in AO that are being carried out by the world's other large telescope observatories. In order to maintain our leadership we must pursue new AO systems and the instrumentation to exploit them. Our consideration of the competitive landscape has found that there are major opportunities for the Observatory to assert its continued leadership through an ambitious program that will address clearly differentiable and unique objectives for AO on the Keck telescopes.

Over the past six months we have examined a broad range of key science areas in order to identify the most compelling future science goals of our community and to determine what is needed to realize these goals. As a result we propose to begin the design phase of a next generation adaptive optics (NGAO) system that will provide a powerful new suite of capabilities:

- Near diffraction-limited performance at infrared wavelengths, producing an AO point spread function with unprecedented precision, stability and contrast;
- Vastly increased sky coverage and multiplexing capability, enabling a much broader range of science programs; and
- AO correction into the red portion of the visible spectrum (0.6-1.0 μm), delivering the highest angular resolution images available from any filled aperture telescope.

The proposed concept will be a broad and powerful facility with the potential to achieve major advances in astrophysics. NGAO will provide dramatic gains in solar system and galactic science where AO has already demonstrated a strong scientific impact. NGAO will allow for extraordinary advances in extragalactic astronomy, far beyond the initial gains being made now with the Observatory's current AO systems.

Our proposal lays out a point-design for implementing the NGAO system, and outlines a series of technical studies and cost-benefit trades that will be completed in the next phase of system design. It also describes a proposed suite of instruments, with highest priority given to narrow-field near

infrared and visible imagers, and to a near-infrared deployable integral field spectrograph with multi-object capability.

The proposed NGAO system is similar in concept, but notably less sweeping in scope, to systems proposed for the Thirty Meter Telescope (TMT). As such it will benefit from the feasibility studies already completed and being conducted for the TMT. Moreover, by implementing NGAO at least several years ahead of analogous TMT instruments, our community will gain both scientific and technical experience that can materially help future TMT efforts.

The success of the current laser guide star AO system at the Observatory is just a hint of the benefits that will accrue from the continued development of AO. A next generation AO system will be a technically challenging project with significant funding requirements. It would be easy to conclude that the level of risk is too high, and that we should find ways to keep pace with the advancing technology of astronomy in fields other than AO. However, the benefits to science from an ambitious development in AO are tremendous, and these developments are the key to realizing the full potential of the Keck telescopes. Beginning the process of developing AO capability suited to the broad range of high impact scientific problems discussed in this proposal could be the best and most important way to secure the future of the Observatory and our community.

EXECUTIVE SUMMARY

1.1 Introduction

The Keck telescopes are the world's largest optical and infrared telescopes. They represent a major resource for astronomical observation, one that has been highly productive and continues to be in great demand. Because of their large apertures the Keck telescopes offer the highest potential sensitivity and angular resolution currently available. Unfortunately, without a means to overcome the performance limits imposed by the turbulence of the earth's atmosphere much of the superiority of the Keck telescopes would remain unrealized.

Adaptive optics (AO) is now an established and fundamental technique for overcoming the performance limiting effects of atmospheric turbulence. The W. M. Keck Observatory (WMKO) has been among the leaders in the application of AO and the benefits to astronomy have been clearly demonstrated by the many discoveries that have been made using AO on the Keck telescopes. The importance of achieving the full potential of the Keck telescopes is recognized in the Observatory's strategic plan which identifies leadership in high angular resolution astronomy as a key long-term goal.

At this time we face a number of challenges to our leadership in high angular resolution astronomy because of the aggressive development efforts in AO that are being carried out by the world's other large telescope observatories. In addition, as we look towards the future we can anticipate the construction of even larger telescopes, leading to the end of the era where the shear size of our telescopes give us an inevitable lead over our competitors.

In order to maintain our leadership we must take the next steps in the development of AO systems and the next steps in the development of instrumentation to exploit these systems. Our consideration of the competitive landscape has found that there are major opportunities for the Observatory to assert its continued leadership through an ambitious development program that will address clearly differentiable and unique objectives for AO on the Keck telescopes.

Our focal point for this effort is called the "Next Generation Adaptive Optics" system or NGAO. This next generation system will offer significant improvements over the capabilities of our present AO systems and will greatly expand the range of science problems that can be addressed with AO. NGAO will provide new and powerful capabilities:

- Near diffraction-limited performance at infrared wavelengths, producing an AO point spread function with unprecedented precision, stability and contrast;
- Vastly increased sky coverage and multiplexing capability, enabling a much broader range of science programs; and
- AO correction into the red portion of the visible spectrum (0.6-1.0 μm), delivering the highest angular resolution images available from any filled aperture telescope.

With the introduction of laser guide star (LGS) AO we have seen the beginning of wider AO use in our observing community. A key motivation of our desire to develop NGAO is our understanding that there is level of performance that we can achieve above which an AO system can begin to address a much broader range of science programs, increasing the momentum that has already begun with LGS AO and moving high angular resolution astronomy beyond being a specialized tool restricted to a narrow range of targets, to a progressively more ubiquitous tool meeting the demands of almost any science program.

In the science cases explored in this proposal we have worked to expand the range of science that we believe should be done with AO. The science requirements for the NGAO system are based on a range of science cases that illustrate the potential for NGAO to expand into new fields as well as the dramatic advances that are possible in the fields where AO is already an established observing tool. The example observations explored in each of the science cases demonstrate the considerable scientific potential of improved AO system performance and suggest that if the performance levels established in the science requirements can be achieved there are dramatic opportunities for new and exciting scientific results.

From a competitive point of view, extending the application of AO into the visible wavelengths will open new territory for high angular resolution astronomy, a territory where we can once again be the first to produce scientific results. In addition, while future extremely large telescopes will have AO systems from the beginning, achieving diffraction-limited correction in the infrared on these telescopes will be at least as difficult as achieving visible wavelength correction on the Keck telescopes, making it unlikely that they will pursue visible wavelength AO capability. This will provide a long-term opportunity for the Observatory, even after the construction of much larger telescopes.

Visible wavelength AO capabilities will become increasingly important in an era when the Hubble Space Telescope is no longer available. Today, most users of AO couple their ground-based near-infrared observations with Hubble's visible-light data. But in approximately five years Hubble will no longer exist, and astronomers will be sorely in need of a high angular resolution visible-wavelength capability on the ground.

The nature of the opportunity presented by NGAO is technically challenging and therefore risky. In this regard we have attempted to mitigate some of that risk by examining the feasibility of meeting the science requirements for a broader application of AO at the Observatory. We have concluded that we should proceed to carry out a system design phase effort that will result in a fuller understanding of the achievable performance levels, the technical risks and the estimated schedule and cost to completion. We also want to emphasize that the current concept for NGAO is not the first of its kind, it is similar in concept, but less sweeping in scope when compared to the AO systems proposed for larger telescopes such as the TMT, and it is important to note that NGAO is accompanied by a much lower risk suite of instruments.

It will be necessary to carefully assess the expected performance of the NGAO system at every design review milestone and to maintain a process of involving our scientific community in the goals and requirements for the new system and its instrumentation. The science cases for NGAO are very strong, and there is a strong possibility that the system is technically feasible. NGAO has the potential to have a major positive impact on the scientific leadership of our astronomical community, and it is an opportunity to continue to do what we do best: get there first.

1.2 Large Telescope Adaptive Optics

At the present time the world's other large telescope observatories (Gemini, Subaru, LBT, and ESO) are developing a total of ten new AO systems all of which represent efforts towards second-generation AO systems and instrumentation. This formidable competition is led by ESO where a steady increase in funding since 2004 has resulted in significantly higher levels of spending on AO compared to US observatories. Figure 1 shows an estimate of the current and future funding levels for astronomical AO recently complied by J. Frogel of AURA, and it should be noted that this estimate does not include the additional ~ $2M per year from the European Union's Opticon program.

Interestingly, with the exception of the Gemini MCAO system, all of the second-generation AO systems are directed either at seeing improvements, primarily ground layer AO, or extremely high contrast "planet finding" AO. None of the second-generation AO developments are directed at achieving general purpose near diffraction-limited (high Strehl) performance in the infrared, either over a narrow field or a wide field. Likewise, no large telescopes are currently attempting to extend high-order AO correction to visible wavelengths.

While the science possible with extremely high contrast systems is of great interest, the approach being taken to optimize the performance of these systems defines them as specialized niche instruments with a finite lifetime based on their sensitivity and the number of targets available. Ground-layer AO systems are expected to improve observing efficiency and to make significant improvements in the angular resolution obtained with wide-field imagers, but they will not deliver the truly diffraction-limited performance needed for many fundamental problems in solar system, galactic and extra-galactic science.

We believe that the current direction of AO development at other large telescopes creates a well-defined opportunity to pursue high performance AO with the emphasis on diffraction-limited performance over narrow and moderate fields. NGAO on the Keck II telescope will enable a wide range of science that depends on the precision possible with higher resolution and the sensitivity gains that accompany near diffraction-limited imaging in the near infrared. Achieving this performance in the infrared will also give us a system capable of high angular resolution at the red end of the visible wavelength bands. WMKO can be the first large telescope observatory to offer these capabilities, thereby creating many opportunities for future breakthrough discoveries.

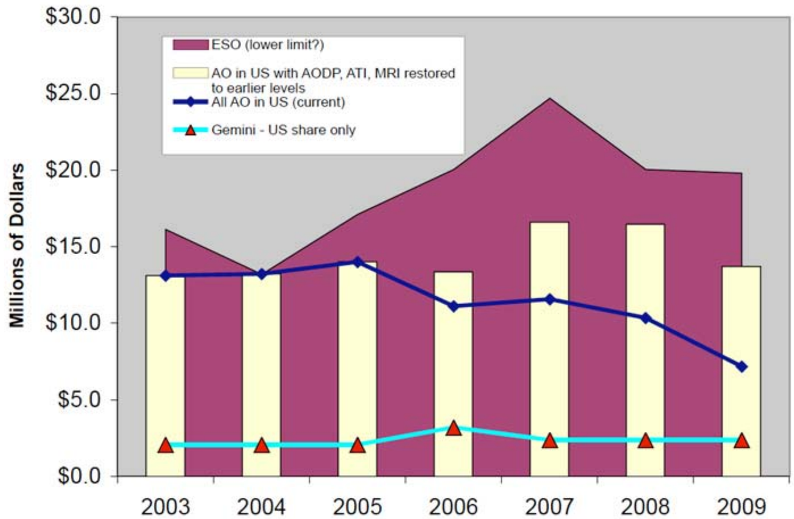

Figure 1: European and US investment in astronomical AO.

1.3 Science Overview

The central and most important reason for our belief that NGAO is the right major development priority for WMKO is found in the results of an intensive effort to identify and understand the science potential for AO at the Observatory. Our approach has been to quantitatively develop a limited number of science cases, drawn from areas of high interest to the WMKO scientific community and spanning the range of modern observational astronomy. While we have not tried to describe every kind of science of interest to our community, the results of our focused study have demonstrated the breath of new opportunities within reach of NGAO. It is also clear that the right NGAO system will be of great appeal to a broad community of users. This will continue the advance of AO from being a specialized tool to a fundamental Observatory facility capable of meeting the demands of many science programs.

The three broad areas of science considered here: extragalactic, galactic and solar system science, are all reflected to varying degrees in the current time allocations for NGS and LGS AO observing at WMKO. NGS AO science has largely been restricted to solar system and galactic science, which has produced a large number of high impact results from the improved angular resolution and sensitivity possible with AO. The current Keck II single laser guide star AO system is opening the door to high angular resolution extragalactic astronomy, but this system is limited to the near-IR wavelengths and its performance is limited by modest Strehl and a small field of view.

Extending the benefits of LGS AO to a greater range of science comes down to three important characteristics for a next generation AO system: (1) high Strehl near-IR performance (near diffraction-limited) producing a stable, high contrast point spread function (PSF); (2) correction at visible wavelengths to achieve the highest angular resolutions and access key physical diagnostics; and (3) multiplexing capability over narrow to moderate fields of view.

In the following sections we summarize key science cases from each of the major science areas discussed in the proposal and identify the benefits that NGAO will bring to each topic. It is important to keep in mind that these science cases are only a limited set of the possible topics in each area. Within the scope of this proposal we have selected these cases based on the high level of interest from our community, the availability of astronomers interested in those areas and willing to assist us in the analysis and simulation of science with NGAO, and with an eye to including a sufficiently diverse range of cases that we truly challenge the parameter space of a new AO system.

The simulations performed in each of the science cases are based on performance estimates for the NGAO system. These estimates are based on residual error budgets for an initial conceptual design of the NGAO system that was arrived at through a first set of iterations from the science requirements to the technical requirements.

1.3.1 Extragalactic Science

Until the past year, adaptive optics did not have a high impact on extragalactic science. Natural guide star AO systems only provide correction over a very small fraction of the sky (~1%), and thus are largely unsuited to extragalactic science. The recent commissioning of the single LGS AO system on Keck II has been a significant advance for this field. This is demonstrated by the entirely new group of astronomers in the WMKO science community who are flocking to AO, in order to tackle such diverse astronomical systems as extragalactic globular clusters, starburst galaxies, supernovae progenitors, field galaxy mergers, and high-redshift galaxies.

The progression from natural guide star AO to single-laser guide star AO has been a major advance for extragalactic astronomy. However, current NGS and LGS AO systems provide only narrow fields of view due to anisoplanatism. Unlocking many of the fundamental questions in galaxy formation and evolution requires large statistical samples, in order to measure the broad range of physical properties and then to test theoretical models — this central methodology in the field is a very challenging prospect for current AO systems. In addition, current LGS AO is limited to infrared wavelengths; therefore, key astrophysical diagnostics at optical wavelengths are unobtainable.

NGAO will dramatically improve this situation in key ways.

NGAO will have 3 to 6 times better signal to noise ratio for near-infrared spectroscopy and imaging of high-redshift galaxies, thanks to its higher Strehl. This will result in a factor of 9 to 36 times shorter integration time to achieve a required signal-to-noise ratio (SNR). For example, Figure 2 shows a simulation of the performance of an integral field spectrograph observing the z~2 star-forming galaxy BX 1332 from the catalogue of Erb et al. (2004). In this case, NGAO delivers a factor of 3 improvement in SNR. The NGAO system also allows extraction of a velocity map over more than 3 times the area within the galaxy than the current LGS AO system.

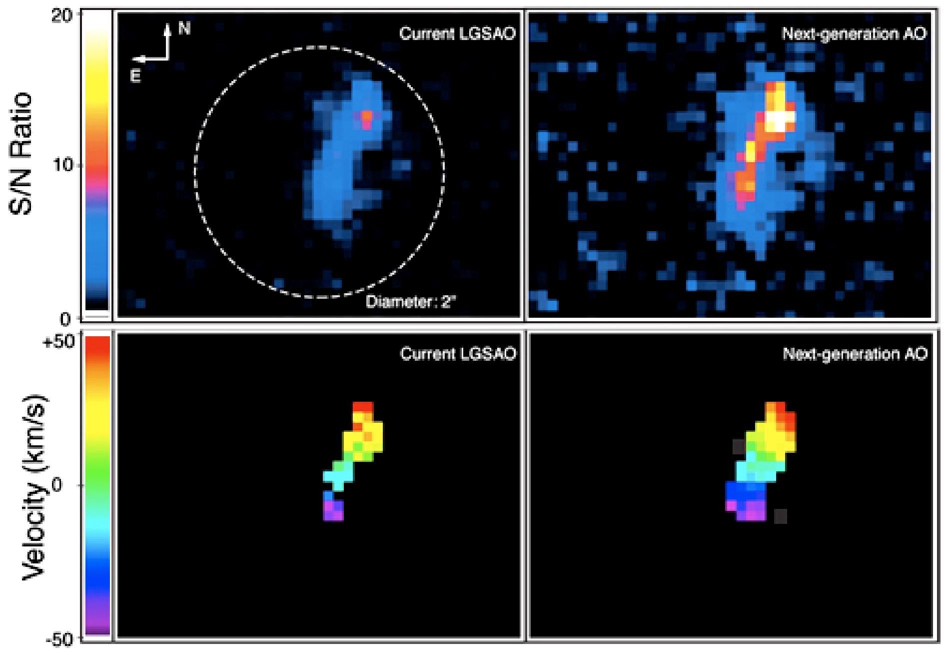

Figure 2: Simulated integral field spectroscopy of z ~2 star-forming galaxy from current AO and NGAO.

For the same exposure time, the planned NGAO system shows a 3x improvement in SNR and a 3x larger area for extraction of the velocity map, enabling large surveys for resolved studies of high redshift galaxy morphology and kinematics.

Spatially resolved spectroscopy of the caliber demonstrated in Figure 2 will provide new insights into the assembly of high-redshift galaxies in the early universe by resolving their internal kinematics, the star formation histories of their major components (bulge/disk), and understanding the role of mergers and AGN.

The wide-field (~2′ diameter) capability delivered by NGAO will be a transformational capability, not possible with current AO. Combined with the aforementioned sensitivity gains, NGAO will enable large multiplex, high angular resolution (i.e. multi-object AO) spectroscopic surveys in practical amounts of telescope time. The surface density of various classes of high-redshift galaxies is in the range of 0.1 to 10's of objects per square arc minute. Since each galaxy subtends an area of at most a few square arc seconds, and since there are large stretches of blank sky between galaxies, the deployment of individual, narrow-field MEMS[1]-fed integral field unit (IFU) spectrographs beneath each galaxy is a perfect application for NGAO, as illustrated in Figure 3.

[1] Micro-electro-mechanical Systems, in this case very small deformable mirror arrays fabricated using integrated circuit technology.

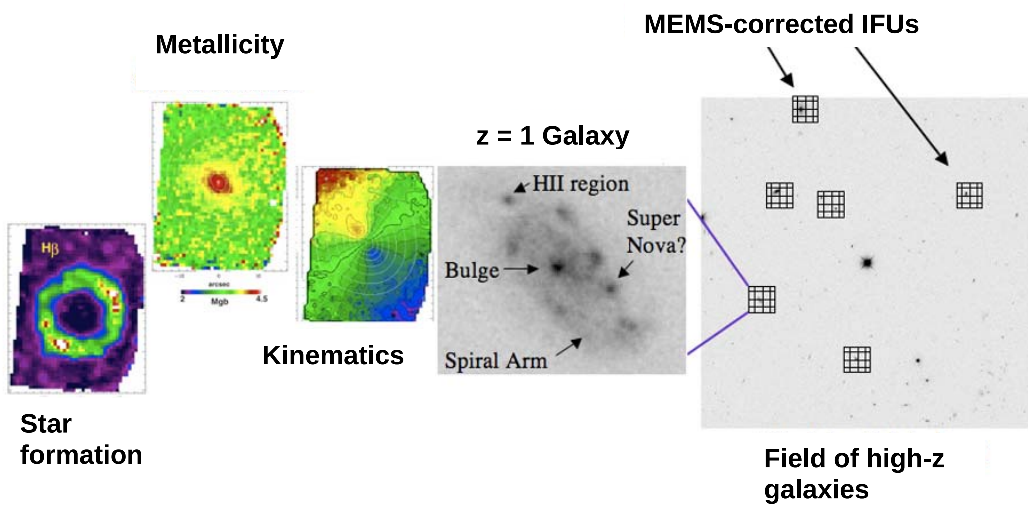

Figure 3: Schematic illustration of the benefits of Multi-Object Adaptive Optics.
Resolved maps of velocity, metallicity, and star formation rate are shown from SAURON IFU data obtained in seeing-limited mode. NGAO will carry out large surveys of high angular resolution spectroscopy for high-redshift galaxies, heretofore impossible with any existing telescope.

Thus, NGAO will substantially improve the study of high-redshift galaxies by making it possible for the first time to do AO surveys of large numbers of galaxies. Moreover, we will be able to focus on selected subclasses of interest and still acquire populous samples; with the multiplexed near-infrared spectroscopy enabled by multi-object AO, we will have access to thousands of high-redshift galaxies. Among other things, this will enable use of the impressive arsenal of spectroscopic diagnostics developed at visible wavelengths for lower-z galaxies. In our science case study, we examined one aspect in detail: use of NGAO to understand the merger history of galaxies in the early universe. We found that the SNR improvement due to NGAO was a significant factor in being able to carry out the necessary measurements on a sufficiently large sample of merging galaxies. We have also studied some of the key extragalactic survey regions (GOODS-N, GOODS-S, and COSMOS) and found that NGAO will be able to cover a substantial fraction of these fields. Therefore NGAO galaxy surveys can take advantage of the enormous multi-wavelength datasets for these fields in order to select targets of interest and to aid in the physical interpretation.

While designs for such multi-object AO instruments on the TMT are considering 20 to 30 deployable MEMS-assisted IFUs, we have settled on a much more modest “sweet spot” for the NGAO system: on the order of a half-dozen deployable IFUs over a field that is about 2′ in diameter. Our motivation for considering only a half-dozen deployable IFU units was initially to lower the cost and the technical risk. However taken together with the improved SNR obtained with NGAO, the proposed modest level of IFU multiplexing will result in a staggering factor of 50 to 200 improvement in overall telescope throughput. These dramatic improvements will strongly distinguish NGAO from all other planned AO systems on 8 to 10 meter telescopes.

In general, the notably higher Strehl and PSF stability compared to current Keck II LGS AO will make NGAO an essential tool for a wide range of extragalactic applications. For instance, our science case simulations show that NGAO will be significantly more sensitive than current LGS AO for studying gravitational lenses and for resolved spectroscopy of both lensed and lensing galaxies. So far the Hubble Space Telescope has been the unchallenged leader in this field, but as shown in Figure 4, a Keck telescope with NGAO is better than HST for these purposes and will dominate the subject. Gravitational lensing, due to either galaxy clusters or individual field galaxies, permits the study of even very high redshift galaxies by magnifying their light and their physical features. AO integral field spectroscopy of lensed galaxies will open the way for high spatial resolution studies of dynamics and chemistry of galaxies in the distant universe and for detection of the first galaxies and sources of reionization at a redshift z > 7 to 8.

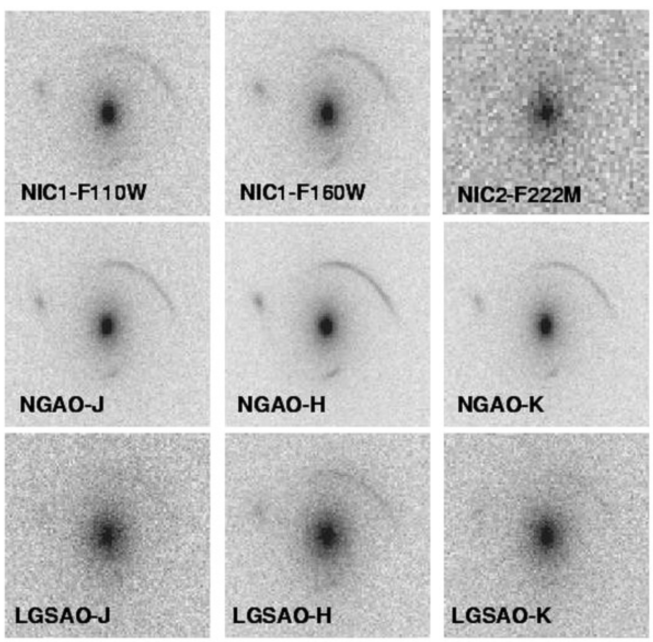

Figure 4: Simulated observations of a gravitational lens from HST-NICMOS (top row), NGAO (middle row) and the current LGS AO system (bottom row).
Each image is 4" on a side and the exposure time is 3600s. The lens is an L elliptical at z=0.8 with a 250 km/s velocity dispersion. The background source is a galaxy at z=7 with 0.05" half light radius, and J H K AB magnitudes of 25, 24.2, 24.4, representing a young population of a few billion solar masses. Note that NGAO is superior in all cases.*

Similarly, the higher Strehl and PSF stability of NGAO will significantly advance our understanding of the formation of AGN, super massive black holes, and their accompanying host galaxies. For detecting black holes in nearby galaxies from (stellar or gas) kinematical measurements, the much improved PSF quality and stability of NGAO compared to current AO will greatly improve the accuracy of black hole masses derived from near-IR observations. In addition, NGAO's optical capability will enable use of the Ca II triplet lines with a PSF core that is narrower than in the near-IR; this will extend the distance out to which the most massive black holes can be detected, thereby boosting the statistics of the M-σ relation for the most massive galaxies. It has become increasingly clear that black holes play a key role in galaxy formation and evolution, the most dramatic evidence being the observed tight correlations between black hole mass and the bulge velocity dispersion of the host galaxy (a.k.a. the "M-σ relation") and between black hole mass and bulge mass. Precision AO observations will be critical in advancing this field over the next decade; with no current spectroscopic capability on HST, AO observations are essentially the only way to pursue dynamical determinations of black hole masses.

In summary, NGAO coupled with a modest six unit deployable IFU spectrograph will offer qualitatively new capabilities for extragalactic astrophysics: factors of 50 to 200 improvement in overall throughput for distant galaxies with point-like substructure; detailed kinematic maps for galaxies at $z > 2$; black-hole mass measurements in a considerably broader array of galaxies; sensitivity to smaller black hole masses; and a genuinely unique capability to exploit gravitational lensing for the study of galaxies at $z > 7$ to 8.

1.3.2 Galactic Science

Galactic science has reaped the rewards from each successive generation of adaptive optics. Natural guide star AO and current single-LGS AO have made numerous significant contributions. However, while galactic science with AO has been prolific, it has only been able to tackle a limited portion of the key science questions. NGAO will be a powerful and broad capability to produce major advances in this field. Its near diffraction-limited performance in the near-IR opens a new realm for observational searches and measurements at high contrast and/or exceptional precision. In addition, NGAO optical imaging will produce the highest angular resolution images from any filled-aperture telescope.

One of the key areas of this field lies in understanding the formation of stars and planets. There is a well-established timeline for the evolution of these objects: from the collapse of their natal molecular cores, to formation of an infalling envelope and a rotating circumstellar disk, to subsequent dissipation/removal of the circumstellar material and the accompanying formation of planets and planetesimals. However, many elements of this simple conceptual paradigm remain to be verified by observation — the timescales are poorly understood, the underlying physical theories are ill-constrained, and the plausible diversity of the outcomes is not known.

The unique combination of high-contrast near-IR imaging (Strehl ratios of 80-90%) 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. Both the Gemini Observatory and ESO are developing highly specialized planet-finding AO systems with extremely high contrast for direct imaging of young planets. These "extreme AO" systems are very powerful, but their design inevitably restricts them to searches around bright, solar-type stars (I=8 to 9 mag).

NGAO will strongly distinguish work at WMKO from all other direct imaging searches planned for large ground-based telescopes. By number, low-mass stars ($<\sim 0.5\ M_{Sun}$) and brown dwarfs dominate any volume-limited sample, and thus these objects may represent the most common hosts of planetary systems. Such cool, optically faint targets will be unobservable with specialized extreme AO systems, but thousands of these in the solar neighborhood will be targeted by NGAO. 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 shows an estimate of the planet detection sensitivity for NGAO.

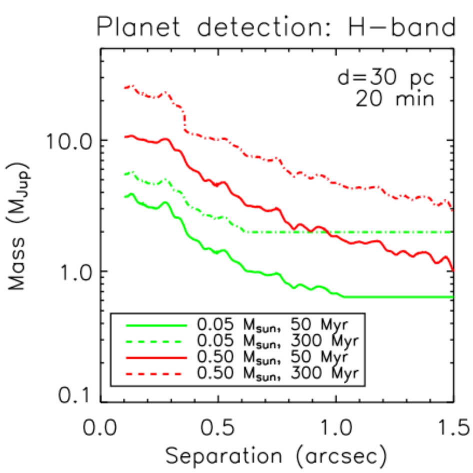

Figure 5: Estimated NGAO sensitivity for direct imaging of planets around low-mass stars (red lines) and brown dwarfs (green lines).

NGAO will be able to search for Jovian-mass companions around large numbers of low-mass stars and brown dwarfs in the solar neighborhood

Direct imaging of extrasolar planets by NGAO would allow us to measure their colors, temperatures, and luminosities, thereby testing theoretical models of planetary evolution and atmospheres. NGAO spectroscopic follow-up will be an important means to characterize the atmospheres of extrasolar planets, which are otherwise essentially inaccessible to spectroscopy. Figure 6 summarizes the relative parameter space explored by NGAO and extreme AO. The complementarity of the two systems is very important: establishing the mass and separation distribution of planets around a wide range of stellar host masses is a key avenue to understanding the planet formation process. The optical faintness of low-mass stars, brown dwarfs and the very youngest stars make them inaccessible to extreme AO systems but excellent targets for NGAO.

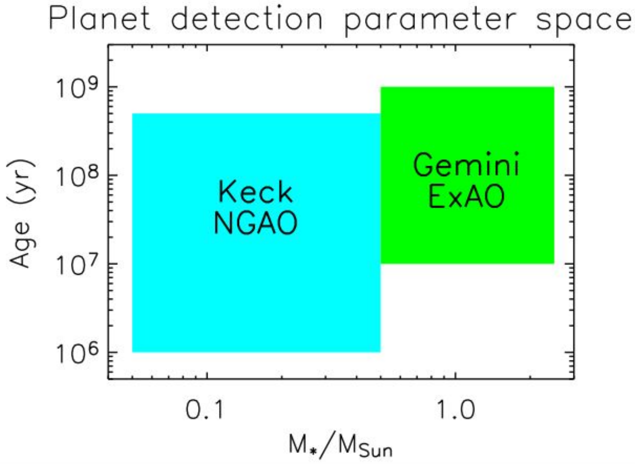

Figure 6: Schematic illustration of the parameter space of NGAO and the Gemini Planet Imager for direct imaging of extrasolar planets.

Furthermore, a Keck telescope with NGAO will be the only large telescope with high-order AO at optical wavelengths, thereby producing the very highest angular resolution from any filled-aperture telescope. One major area of galactic astronomy (among many) that will benefit is the study of debris disks. As the extrasolar analogs of our own asteroid and Kuiper Belts, debris disks provide unique insights into the frequency, properties, and formation of low-mass planets and planetesimals around other stars. So far, resolved imaging of debris disks (through light scattered off their circumstellar dust) has been very limited with AO, restricted to the tiny handful of the brightest, nearest, edge-on disks. In general, scattered light studies are better performed at shorter wavelengths, where the lower sky brightness and favorable dust scattering properties lead to optimal contrast between the parent star and the debris disk. Due to its exceptional angular resolution in the optical, NGAO will be a powerful tool to identify debris disks and study their resolved structure. In particular, observations of disk substructure are a very promising method to detect the presence of low-mass (Neptune-class) planets, otherwise undetectable by direct imaging or radial velocity surveys.

Complementary debris disk surveys by NGAO at near-IR wavelengths will have lower angular resolution but higher PSF stability. This is especially useful for finding the most massive debris disks around stars in young open clusters (>100 pc away), where the disks can be small but very bright. Figure 7 shows a simulation of a massive Kuiper belt analog around a solar-type star in the Pleiades (120 Myr), showing the excellent sensitivity and contrast delivered by NGAO. Such observations will provide the first comprehensive view of what the solar system may have looked like at an early age.

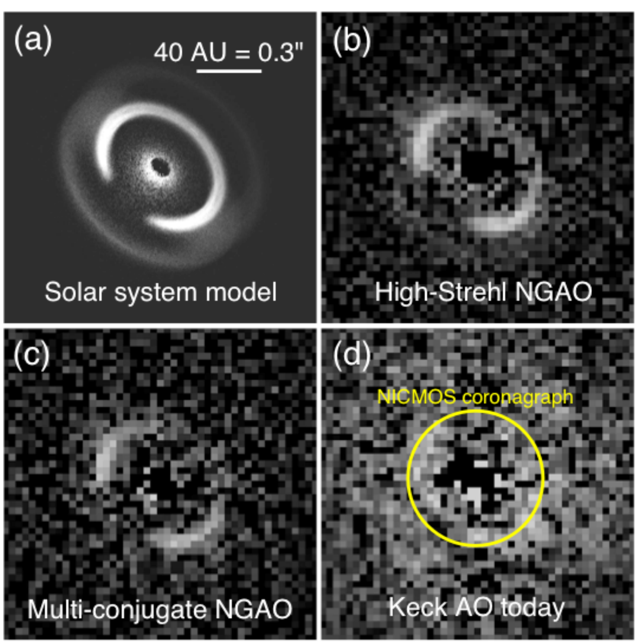

Figure 7: Simulated H-band images of a massive Kuiper belt analog around a solar-type star. *The Strehl ratios of the simulated images are 82% (panel b), 47% (panel c), and 28% (panel d). The AO images are all shown with the same linear grayscale. The size of the smallest coronagraph available on HST is overlaid on panel (d) to illustrate the new phase space that will be opened at <0.3" separations by NGAO.*

Finally, the unprecedented PSF stability and precision of NGAO in the near-IR will open the door to new studies of the Galactic Center region. The improvements in Strehl and angular resolution will reduce the biases in astrometric measurements arising from the stellar confusion limit. Thus, NGAO could allow, for the first time, the detection of relativistic effects that are expected in the presence of a massive black hole. These include prograde precession of stellar orbits around the black hole and inertial frame "dragging" in these orbits due to the black hole's spin. Detection and measurement of these effects will provide a fundamental test of general relativity and help constrain the formation process of the black hole.

The astrometric precision required for these detections is illustrated in Figure 8, assuming a 10-year baseline with 10 epochs per year. Low-order general relativity and extended matter effects are easily detectable (at the >5σ level) with a precision of ~200 μas, while the detection of black hole spin requires either better precision or improved SNR from the observation of multiple high-eccentricity, short-period, stars over multiple orbits. We expect that astrometric precision on the order of 100 μas will be obtained with NGAO.

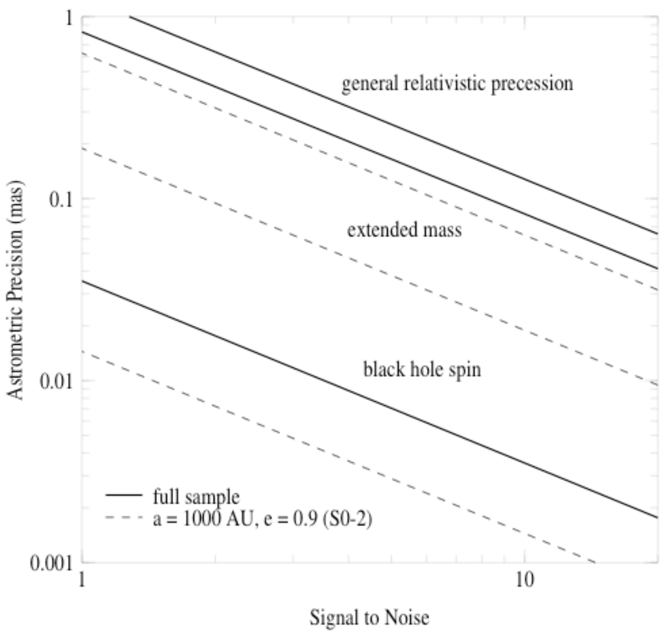

Figure 8: Required astrometric precision for detecting GR effects in the Galactic Center region.
Shown from top to bottom are the astrometric precisions required to detect GR effects associated with relativistic prograde precession, GR effects due to extended mass within the stellar orbits, and frame-dragging effects due to the spin of the BH (based on Weinberg et al. 2005).

This improved astrometry from NGAO will also allow much more accurate measurement of the distance to the Galactic Center. Measurements accurate to ~0.1% are expected and will also allow high precision measurement of the galactic dark matter halo. The expected improvement in measurement accuracy is illustrated in Figure 9, which compares error contours for black hole mass and Galactic Center distance obtainable with the current LGS AO system and the expected performance of NGAO. NGAO will produce more than two orders of magnitude greater precision than current studies; this improvement will not be greatly surpassed even in the future with extremely large telescopes.

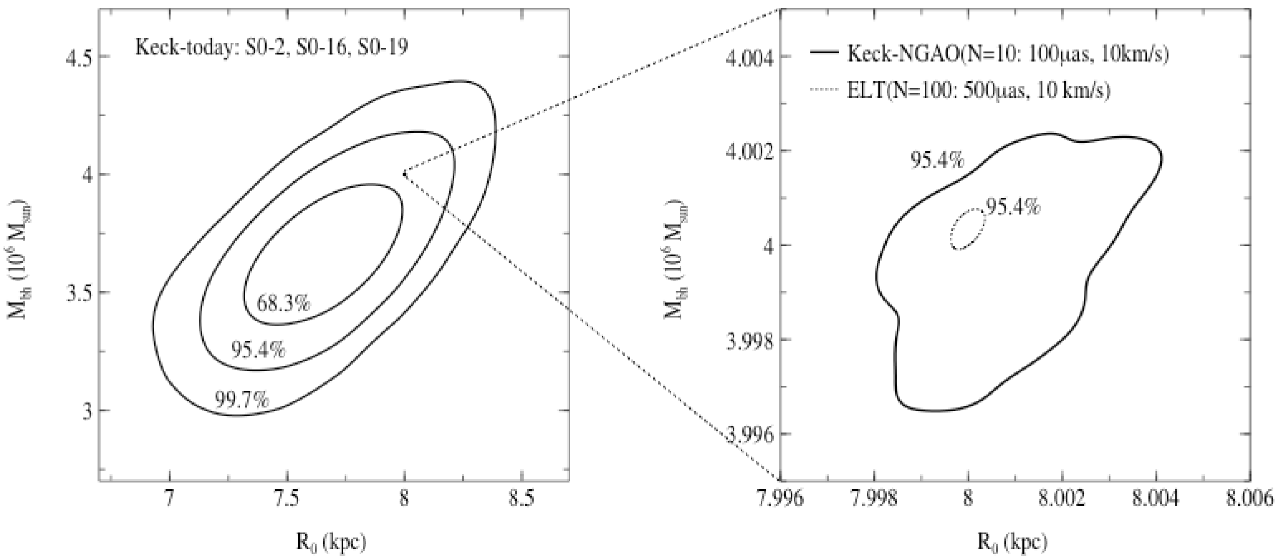

Figure 9: Error contours for black hole mass and Galactic Center distance.
The left panel *shows the current AO constraints for the Keck II AO system and the* right panel *zooms in by a factor of ~100 to show the estimate of future constraints from NGAO (solid line) and a 30 m extremely large telescope (ELT, dotted line). The NGAO and ELT numbers in parentheses are the number of stars that are likely observable and the assumed astrometric and radial velocity errors. The small box in the left panel indicates the size of the NGAO constraint on the scale of the current Keck II AO system constraint.*

1.3.3 Solar System Science

While space missions largely drove early progress in planetary astronomy, we are now in an era where ground-based telescopes have greatly expanded the study of planets, planetary satellites and the asteroid and Kuiper belts. Ground-based telescopes can efficiently perform the regular observations needed for the monitoring of planetary atmospheres and geology, and ground-based telescopes can quickly respond to transient events. The timescales needed for planning and launch of spacecraft are incompatible with the need to respond quickly to transient events. Likewise, the comparatively short observational lifetimes of most space missions are incompatible with the need for regular observations to monitor and understand planetary atmospheres and geology.

AO has already enabled the Keck telescopes to make significant contributions to the study of our solar system. However, the unprecedented angular resolution and increased sensitivity offered by NGAO on a Keck telescope will enable a much broader range of innovative solar system studies, accomplished with multi-wavelength optical/IR imaging and resolved (integral-field) spectroscopy.

The study of the remnants from the formation of our solar system provides insight into the proto-planetary conditions that existed at the time of formation. Such information has been locked into the orbits and properties of asteroids and Kuiper Belt objects. The study of binary (and multiple) objects is one key path to revealing these insights, specifically by studying their kinematics and geological properties. However, there are no space missions currently planned to study these binaries. This important line of inquiry is only accessible to ground-based telescopes equipped with AO.

High angular resolution studies are needed of large samples of binaries to understand how their enormous present-day diversity arose from their formation conditions and subsequent physical evolution, through processes such as disruption and fragmentation. NGAO imaging will allow more precise measurements of sizes and orbital parameters. Well-calibrated size distributions will allow progress in understanding disruption and fragmentation. More precise measurement of sizes is also important to understanding the population of potentially hazardous near earth objects (NEOs). At present, very few NEO sizes are known. Higher sensitivity will increase the number of detections allowing the larger sample sizes needed to establish statistics to anchor and constrain models of solar system formation and evolution.

An example of the gains expected from NGAO is shown in Figure 10. This figure shows a simulated multiple asteroid system based on the recently discovered triple system 87 Sylvia. Two artificial moonlets have been added to the system, one much smaller than the two known moonlets and located between their orbits, and one intermediate in size between the two known moonlets but located closer to the primary. Monte Carlo simulations in our science case show that NGAO optical imaging (R-band) is exceptionally capable of finding such small moonlets, thanks to its high angular resolution. Another figure of merit for NGAO is the increase in the number of observable asteroids. The present AO system has a limiting magnitude of V = 13.5 in NGS mode, resulting in ~1000 observable main-belt asteroids. NGAO is expected to achieve a limiting magnitude of V = 17 or deeper through use of AO-corrected tip-tilt stars, increasing the number to 10% of the known main belt population or ~30,000 objects. This means that interesting, rare sub-classes can be identified (though wide-field all-sky photometric surveys like Pan-STARRS) and targeted for high angular resolution follow-up.

The study of planetary atmospheres and geology is important to understanding the geology of our solar system and also enables a better understanding of how our solar system formed. Titan is an important subject because unlike the other satellites of Saturn it has retained an atmosphere. In the atmosphere of Titan methane plays the role that water does on earth, coupling the surface to the atmosphere in a methane-based meteorological cycle. Given that one year on Titan is ~30 earth years, observing seasonal changes requires many periodic observations. Ground-based telescopes are the central tools for these observations. Space missions such as Cassini have provided very high spatial resolution measurements over a comparatively short time scale, but these observations will require follow up to understand and confirm the implications for longer term seasonal variations. The improved resolution and sensitivity resulting from NGAO will enable greater sensitivity to dynamical variations and improve discrimination between surface features and atmospheric phenomena. Figure 11 compares the performance of the current AO system with simulations of the performance of the NGAO system. The simulation was developed using a high-resolution surface map of Titan from Cassini/ISS at 0.9 µm.

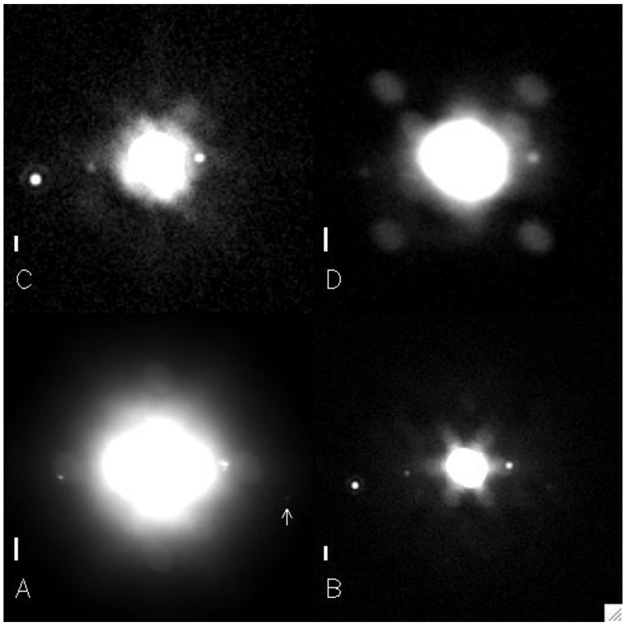

Figure 10: Simulation of a multiple asteroid system based on 87 Sylvia.
The short vertical bar in each image represents 0.1". C is a simulated HST R-band image using ACS; D is a simulated H-band image using the current AO system in NGS mode with NIRC-2. A is a simulated R-band image with NGAO, and B is a simulated H-band image with NGAO.

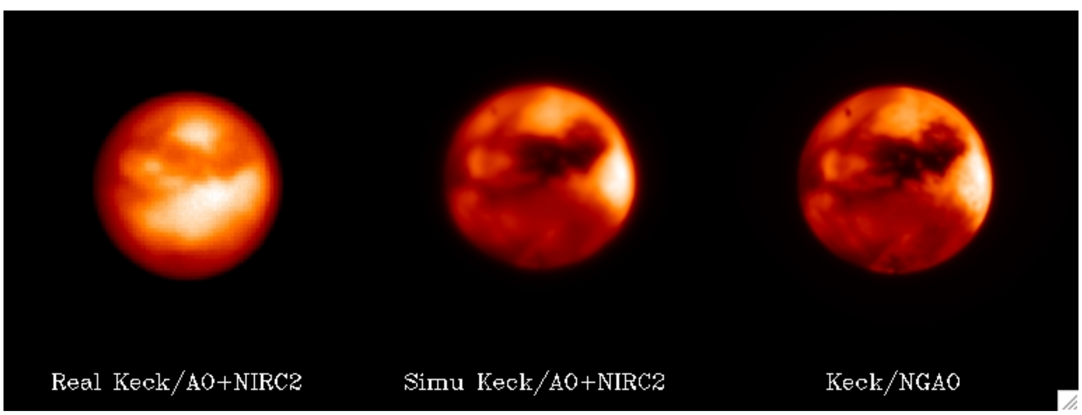

Figure 11: Simulated H-band images of Titan.
The angular diameter of Titan is 0.8". The left hand image is a real image taken with NGS AO and NIRC2. The center image is a simulation of the current AO system performance using NGS AO and NIRC2. The right hand image shows the results obtained from a simulation of NGAO. The simulated images differ from the real observation because of variations in the color of surface features, for instance the bright southern pole is rather dark on our simulation.

The surface of Titan is also of considerable interest. The mechanism for replenishment of the atmospheric methane is not understood, but if releases of methane from the interior of Titan through cryovolcanism are responsible then resurfacing due to this volcanic activity should be observed. The high angular resolution of NGAO should permit observations of released cryovolcanic material. Figure 12 shows a simulated NGAO observation of a new surface feature ~100 km across resulting from a cryovolcanic eruption.

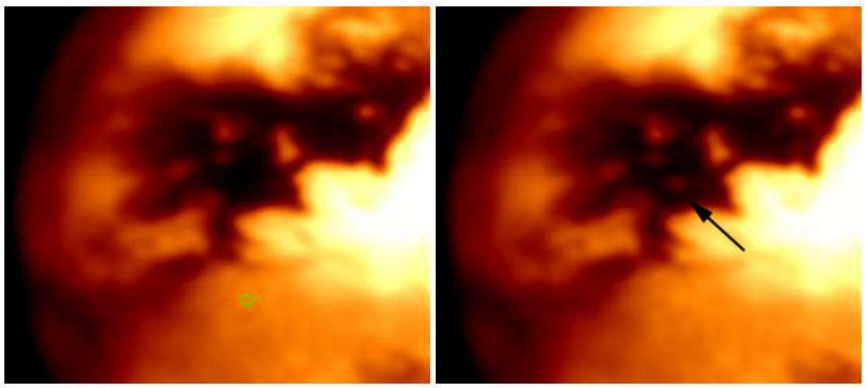

Figure 12: Simulated NGAO image of Titan showing a resurfacing feature ~100 km across. *The left image shows the surface prior to resurfacing and the right image shows the resurfacing feature at the tip of the black arrow.*

1.3.4 Science Requirements

In summarizing the science requirements from each of the science cases discussed in the preceding sections we have identified three key parameters that define the most important characteristics of the NGAO system for each science case. These are wavelength coverage, Strehl and field of view. In addition we have identified specific instrumentation that is needed to support the various kinds of observations in each science case. The combined parameter space needs of the science cases are summarized in Figure 13.

	Optical *narrow field, modest Strehl*	**Near-IR** *narrow field, high Strehl*	**Thermal-NIR** *narrow field, v.high Strehl*	**High Contrast**	**Wide-Field, Multi-Object**
Solar System	**Key**	Yes	Yes	Maybe	-
Galactic	Yes	**Key**	Maybe	**Key**	-
Extragalactic	**Key**	**Key**	-	Yes	**Key**

Figure 13: Science case parameter summary

As Figure 13 shows, all of the science cases share a need for high Strehl near-IR imaging that is substantially better that what is achieved with the best performance of the present LGS AO system.

Multiple science cases in all three areas also require the highest possible angular resolution and this can be achieved with a visible wavelength capability offering moderate Strehl. A number of science cases also share the need for access to the optical wavelengths for spectroscopy and multi-wavelength studies. Many science cases also share a need for integral field spectroscopy for characterization of objects and the measurement of kinematics and radial velocities.

At the detail level various special needs are articulated by particular science cases, particularly the need for high contrast imaging and observing modes such as service observing to allow frequent short duration observations of targets to monitor time variable phenomenon such as weather on Titan or volcanic activity on Io.

1.4 NGAO Technical Overview

1.4.1 Introduction

In this section we present an overview of the architecture, components, and expected performance of a point design for the NGAO system, describe a notional suite of instruments, and describe our approach to the system design phase which includes a number of trade studies needed to determine the optimum architecture and maximize the scientific performance of the system.

The scientific requirements for the NGAO system are challenging but achievable. In developing a proposal for the system design phase of the NGAO system we realized that effort was needed to provide a reasonable starting point for simulations of the performance of NGAO for the various science cases. This required us to make an initial pass through the key iterative cycle of the system design process and resulted in the point design presented in the proposal. The system design cycle consists of considering the science requirements and their technical implications, conceiving of a system architecture to meet those requirements, assessing the performance that such a system might deliver and then repeating as required while considering a number of engineering trade-offs to arrive at the best architecture that will meet the science requirements while minimizing technical and cost risk. The point design described in this section is intended to demonstrate the feasibility of meeting the science requirements and is not intended to represent the optimal system architecture.

The key aspects of the proposed NGAO system represented by the point design that distinguish it from the current Keck II LGS AO system are the following:

- Use of multiple laser guide stars to do tomographic wavefront sensing of the entire volume of turbulence above the telescope. This overcomes the cone effect and allows an AO-corrected field of view that is several times wider than current AO systems.

- Use of infrared tip-tilt stars. Because of the wider field of view enabled by tomography, the tip-tilt stars will be partially AO-corrected. The result will be a higher fraction of the sky accessible to the NGAO system.
- Lower rms wavefront error, enabling considerably higher Strehl performance than the current LGS AO system. With NGAO we expect Strehl performance at J band that is comparable with today's performance at K band, and modest but still decent Strehl in the red part of the visible spectrum.
- Use of deployable IFUs for multi-object spectroscopy in the near-IR.

1.4.2 NGAO Architecture

From the science requirements we have established that the NGAO system should have the following characteristics:

- Wavelength coverage from ~0.6 μm to 5.3 μm
- Near diffraction-limited AO correction in the near-IR (high Strehl)
- Modest Strehl for visible observations (0.60-1.0 μm)
- High sky coverage for AO correction
- Ability to multiplex AO observations (observe many targets at once) within a field of regard of a few arc minutes
- High optical and IR transmission
- Low thermal background in the near-IR
- Calibration and control of AO systematic effects on observations

The AO system architecture of the point design is illustrated in schematic form in Figure 14. The NGAO system will employ multiple laser guide stars in conjunction with tomographic reconstruction of the three dimensional turbulence structure above the telescope. This allows the AO system to overcome focal anisoplanatism, and provides partial correction in the infrared of the natural reference stars needed for tip/tilt and other low-order correction. Tomography is required in order to employ either multi-conjugate AO (MCAO) or multi-object AO (MOAO), two alternative techniques that will allow multiplex observing (multi-object integral field spectroscopy) over fields wider than the isoplanatic angle.

As shown in Figure 14 the NGAO system consists of three major components, the AO system and instruments contained within an AO enclosure, a laser enclosure containing lasers operating at a wavelength of 589 nm to create multiple laser guide stars by excitation of the mesospheric sodium layer, and a laser launch telescope facility mounted at the top end of the telescope to project the multiple laser outputs into the sky.

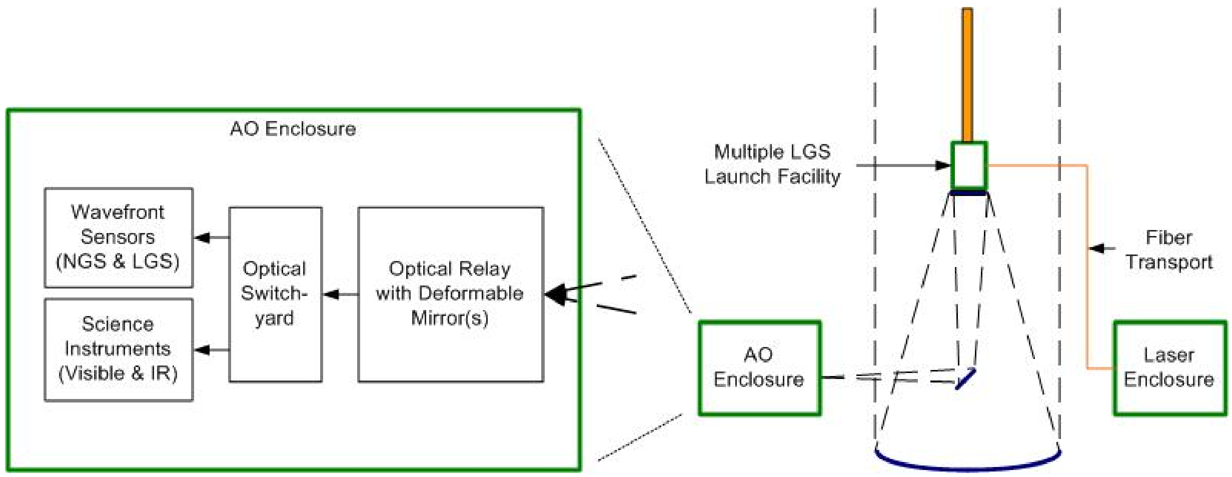

Figure 14: NGAO Architecture

1.4.3 Laser Guide Stars

The NGAO point design uses 5 laser guide stars arranged as shown in Figure 15. This figure illustrates the NGAO field as seen from the focal plane of the telescope. One laser guide star is located at the center of the field and the other four are located at the corners of a square. The positions of the four corners may be simultaneously adjusted along radial lines from the center to expand or contract the LGS asterism. A larger asterism pattern will allow correction over wider fields at the expense of Strehl performance.

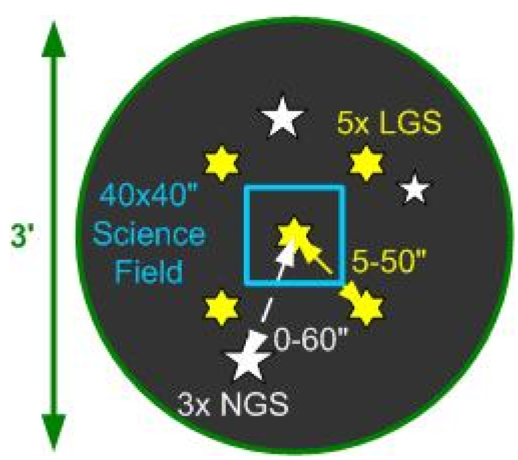

Figure 15: NGAO transmitted field showing LGS asterism, NGS and science field.
(Not to scale)

The exact amount of laser power required will depend on the choice of laser and its coupling efficiency to the mesospheric sodium atoms. Using performance levels similar to those demonstrated in recent tests with the Gemini North mode locked CW laser, we expect that a total of 150 W of optical power at 589 nm will be required (~30 W per guide star). A laser system capable of producing this power level is currently under development for the Gemini South telescope. This laser will be completed in the first half of 2007. In addition, the Starfire Optical Range is currently operating a 50 watt CW laser that would fulfill our requirements, and lasers of this type could also be used for NGAO. We do not see laser availability as a critical issue, but lasers will be a significant cost factor.

1.4.4 Tip/Tilt Sensing

The point design utilizes near-infrared wavefront sensors for tip/tilt sensing. This increases the number of useable natural reference stars, and allows partial correction of the reference stars by the AO system for improved tip/tilt performance and higher sky coverage fraction. Multiple tip/tilt sensors (three in the point design) will be used to sense multiple tip/tilt stars in order to reduce the effects of tip/tilt error over the field.

1.4.5 AO Relay Configuration

As shown in Figure 14 the AO enclosure contains an optical relay system with one or more deformable mirrors, an optical "switchyard", NGS and LGS wavefront sensors, and the science instruments. The AO enclosure provides a dust free environment for the AO system and instruments and also cools the AO relay optics and optical switchyard to –15 ºC to reduce emissivity and thermal backgrounds.

The optical switchyard is used to perform two functions: splitting of the AO relay output into science and wavefront sensing paths, and selection of the desired science instrument. The system is conceived as supporting multiple science instruments and allowing relatively quick switching between instruments.

The number of deformable mirrors required is driven by the approach to achieving wider field AO correction. Most of the science cases in the Solar System and Galactic areas have requirements for relatively small fields of view that are close to the isoplanatic patch size (~10″). For these applications the target density on the sky is low so that only one target will be observed at a time. It will be possible to correct the wavefront for this single line of sight with one deformable mirror. However, most of the extragalactic science cases need the ability to perform multi-object observations over a field of regard considerably larger than the isoplanatic angle.

In order to support the wider-field multi-object mode, we will need to adopt an architecture capable of either providing correction over a larger contiguous field of view, or over multiple smaller fields at the same time. MCAO uses two or more deformable mirrors conjugated to various altitudes in order to correct individual turbulent layers in the atmosphere, resulting in correction across a contiguous field of view. MOAO uses separate deformable mirrors for each science field to provide AO correction for each science object individually, without correcting the regions in between. Our point design has focused on MOAO options.

A schematic of a possible MOAO configuration is shown in Figure 16. The first deformable mirror, located immediately after the telescope focus, provides low order wavefront correction and partial correction to the infrared tip-tilt stars. A second deformable mirror, driven in open loop by the tomography computer, provides the high order correction.

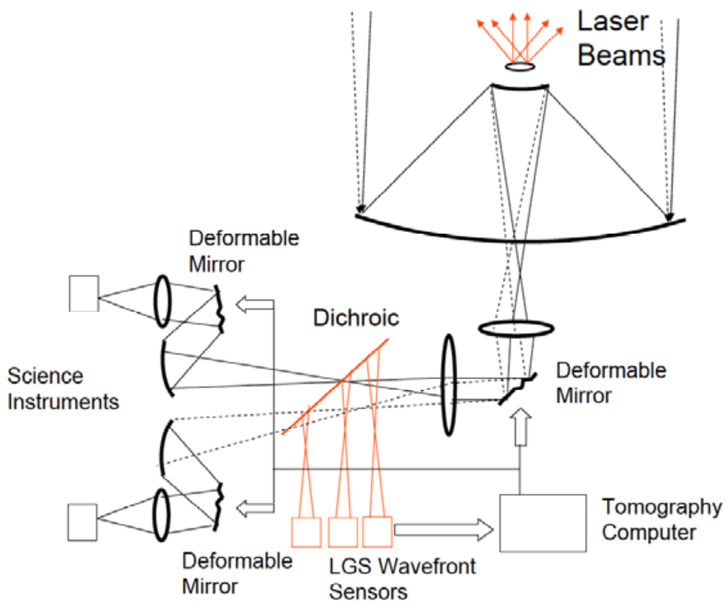

Figure 16: MOAO optical schematic

The optical relay for a MOAO configuration would employ a single, high-stroke deformable mirror with ~1000 actuators. For multiplex operation each science field in an instrument such as a deployable IFU would also be equipped with a MEMS deformable mirror. This mirror would provide low stroke, high order wavefront correction.

If an MCAO system were to be implemented, then instead of the individual MEMS mirrors a second large DM with ~1000 actuators would be added to the relay at a location in the optical path conjugate to a second altitude. This would provide a wider field of correction for multiplex operation.

1.4.6 NGAO Performance

Initial performance estimates for the main science cases we have considered for NGAO are summarized in Table 1. For comparison, note that the current LGS AO system at WMKO has a wavefront error of approximately 360 nm using a bright tip-tilt star. Thus the NGAO system's performance is significantly better than current Keck II LGS AO for all of the science cases.

Table 1: NGAO performance summary for several key science cases.

Science Case	AO mode	Seeing	Field of View (″)	Wavefront Error (nm rms) and Tip-tilt Blur (mas)	Corresponding Guide Star Brightness or Sky Coverage Fraction
1. "Best-conditions" narrow-field	5 LGS	Superior	2"	93	20%
2. Io	1 NGS	Median	1"	125	$M_V = 5.5$
3. Kuiper Belt Object (KBO)	5 LGS	Median	2"	131	$M_H = 15.75$
4. Galactic Center (GC)	5 LGS	Median	10"	182	$M_H = 8.8$ (IRS 7)
5. Field Galaxies (case 1; imaging)	5 LGS	Median	2"	173 + 6 mas	30%
6. GOODS-N Field (imaging)	5 LGS	Median	2"	218+16 mas	20% of GOODS-N
7. Field Galaxies (case 2; d-IFU)	5 LGS	Median	2"	173+30 mas	90%
8. GOODS-N Field (d-IFU)	5 LGS	Median	2"	H-band FWHM ≤ 50 mas	75% of GOODS-N

Whereas high-order wavefront errors take energy from the diffraction limited core and put it into the seeing-limited halo, the dominant effect of tip-tilt errors is to blur the diffraction-limited core. Table 1 portrays the interplay between high-order error and tip-tilt blurring in several different ways. The wavefront error column in rows 1-4 combines high-order error with the equivalent rms wavefront error (in nm) arising from tip/tilt. The latter is initially calculated in units of milli-arc seconds (mas) of residual tip/tilt to arrive at a Strehl ratio due to tip/tilt, and then converted into an equivalent rms wavefront error for H-band. For rows 5-7 in Table 1 we have called out the high-order wavefront error terms and the tip/tilt contributions separately. For a different way to express the information for the GOODS-S deep field, in row 8 we have summarized the H-band performance by stating the overall FWHM due to high-order wavefront errors plus tip-tilt blurring.

For spectroscopy, high-redshift extragalactic science with NGAO is best optimized for so-called “spaxel” (IFU sample) scales of 50-100 mas, since the highest SNRs for high-redshift galaxies are achieved with relatively large IFU spaxels (Steidel, Law and Erb 2006). Because this optimum IFU spaxel size is large compared with the diffraction limit, even relatively severe tip/tilt blurring (relative to the diffraction limit) will not affect spectrograph performance, as long as the blurring remains small compared to the IFU spaxel scale of 100 mas. During the system design phase, we plan to analyze sky coverage for IFU science in more detail using ensquared energy as a more pointed performance metric for IFU spectroscopy. The bottom row of Table 1 shows that for extragalactic IFU science, even in GOODS-N (the most demanding deep field) the sky coverage for which the FWHM is less than 50 mas is quite high (~75%). This means that the majority of GOODS-N would be accessible for study with the NGAO system.

As shown in Table 1 the rms wavefront error predicted for NGAO is typically in the 120 to 180 nm range depending on the observation being performed. Figure 17 shows the resulting Strehl versus wavelength for the range predicted for NGAO with that of the current Keck II AO system (NGS 250 nm and LGS 400 nm).

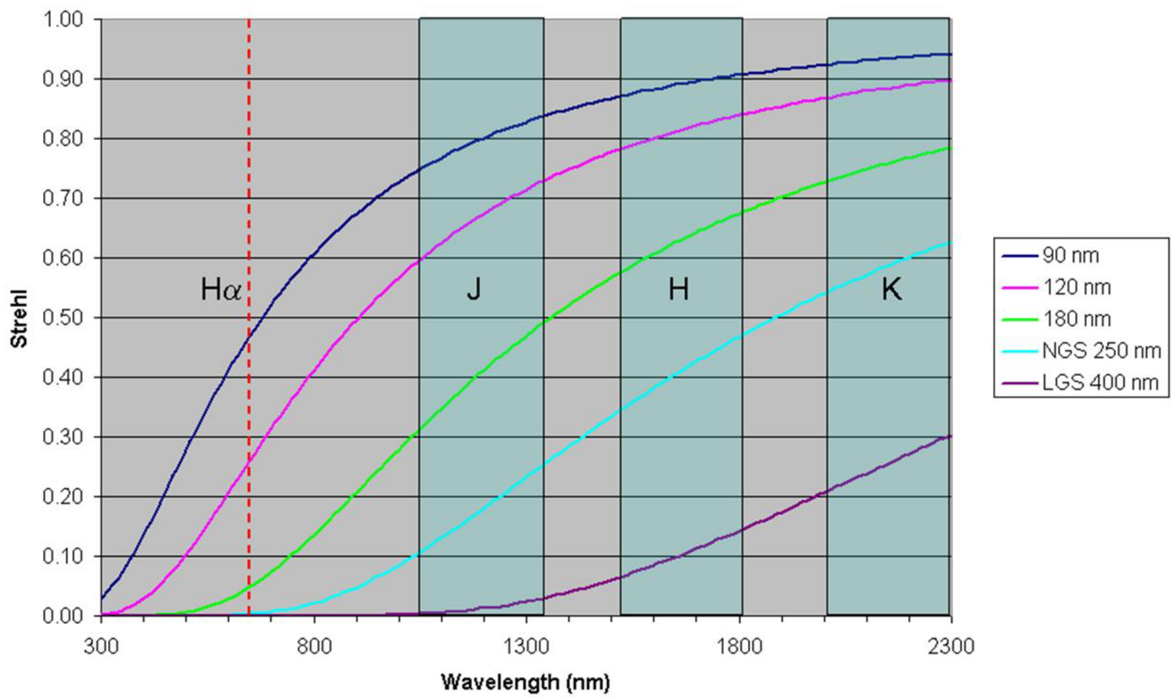

Figure 17:Strehl versus wavelength as a function of rms wavefront error.

A further appreciation for the expected performance of NGAO can be gained from Figure 18 and Figure 19.

Estimated NGAO performance for an on-axis narrow field case such as a typical Kuiper Belt Object (KBO) observation is shown in Figure 18 as a function of science target brightness, for a variety of sky coverage fractions. The optimal choice between target and field tip-tilt stars was used to produce this plot (the science target itself would generally be used as a tip-tilt star for $M_H \leq 17$, whereas field stars are used for fainter objects). A classically scheduled KBO observing program (e.g., one in which telescope allocations are made in quanta of full-nights) would likely follow the behavior of the orange 30% sky coverage curve, yielding H-band Strehls > 50%.

One bottom line from Figure 18 is that almost every infrared source catalogued by 2MASS can be observed with high Strehl by the NGAO system (see the region in Figure 18 brighter than H=15).

A second bottom line is that for <u>any</u> given sky coverage fraction, the H-band Strehl with NGAO is <u>far</u> higher than with current LGS AO (typical H-band Strehls today are 10-15% for 50% sky coverage).

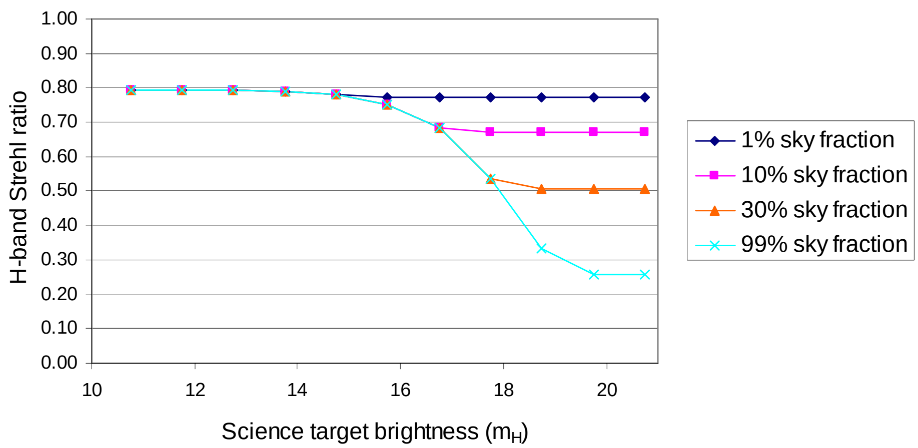

Figure 18: NGAO performance versus target brightness with b = 30° and zenith angle = 30° in median seeing.

The estimated performance of NGAO for Galactic Center observations is shown in Figure 19, which presents the variation in H-band Strehl ratio as a function of seeing conditions. Despite the low elevation angle of the Galactic Center as seen from Mauna Kea, H-band Strehl remains higher than 30% whenever the seeing is better than 1″ at 0.5 µm. For the first time this will open up all of the H-band to Galactic Center observations (not at all feasible previously at WMKO, due to the low elevation angle), leading to improved astrometric accuracy for tracing the orbits of stars around Sag A*. Under median seeing conditions the Strehl for Galactic Center observations is dominated by high-order wavefront measurement error. The Galactic Center science case would benefit from increasing the laser power above the nominal value of 150 W. Cost-benefit analyses of increased laser power will be carried out during the system design phase.

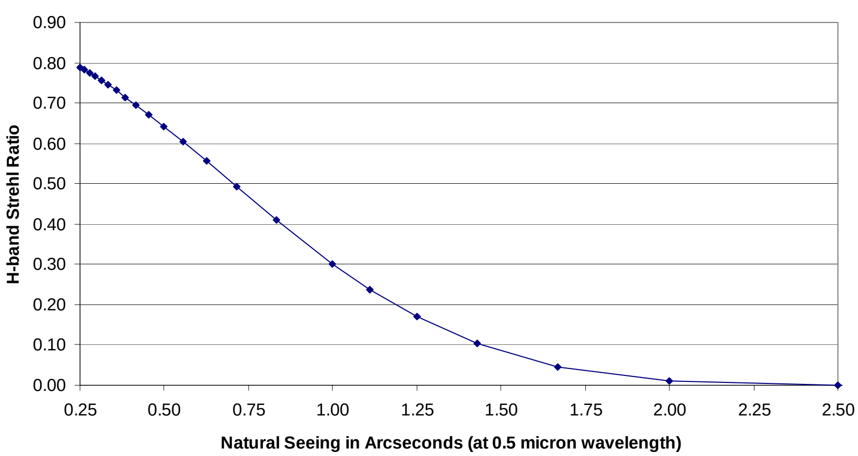

Figure 19: NGAO performance versus seeing for a Galactic Center observation, using LGS mode with IRS7 as the tip/tilt star.

Next we focus on NGAO performance for extragalactic science. Figure 20 shows predicted NGAO H-band performance versus sky coverage fraction, for different combinations of galactic latitude, b, and zenith angle, z. The average over the celestial sphere (the all-galaxy average) is also shown. The "all-sky average" curve shows that H-band Strehl ratios ≥ 50% will be readily achievable anywhere the elevation angle is 30 degrees or less. This is a spectacular improvement over current LGS AO, for which typical H-band Strehls are 10-15%.

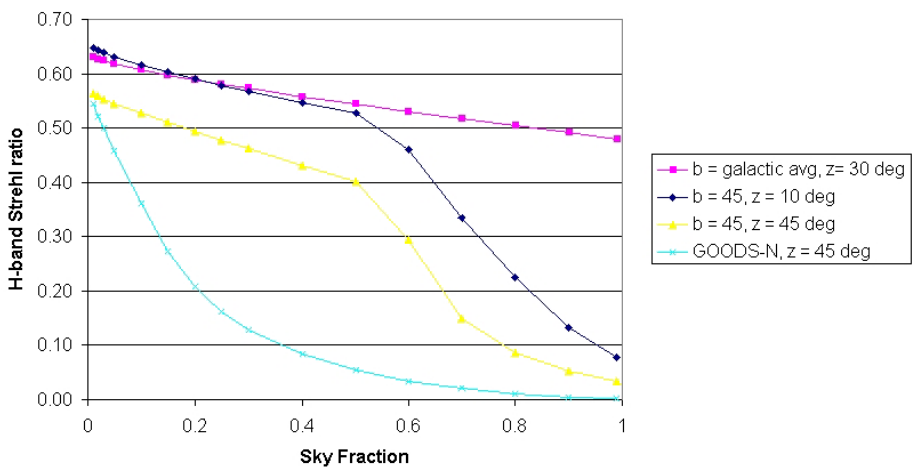

Figure 20: NGAO H-band performance versus sky fraction, for different zenith angles.

The knee in the b = 45º, z = 10º curve is due to the limit on the field of regard established for the initial NGAO point design. In this particular case, for the highest levels of sky coverage it would be preferable to use tip/tilt stars wider than 150″ radius. In the system design phase we will pursue trade studies to optimize the field of regard for tip-tilt guide star acquisition.

Note in Figure 20 that the GOODS-N field, which contains the Hubble Deep Field North and has very few bright stars, shows a much lower than average sky coverage fraction. This is the most stressing case we have analyzed to date.

In the case of extragalactic science, tip/tilt errors dominate the error budgets for high sky coverage cases because bright tip-tilt stars are relatively scarce. Figure 21 shows that the image FWHM is 50 mas or less over about 80% of the GOODS-N field. Since studies show that the 100 mas scale is the preferred spaxel scale for IFU sensitivity at WMKO, we conclude that our NGAO point design would be able to reach a large fraction of GOODS-N for IFU applications. This is far superior to the sky coverage achievable in these fields using the current LGS AO system, because the NGAO system will use infrared tip-tilt stars that can be AO-corrected.

As we explained above, the most relevant performance metric for spectroscopy is not total Strehl but the long-exposure ensquared energy in a given spatial sample (effectively the "slit" or spaxel of the IFU spectrometer). Good high order Strehl correction is needed to prevent light from being scattered throughout the seeing disk (500 mas) but once a diffraction-limited PSF core is placed within the spaxel there is considerable tolerance for tip-tilt error.

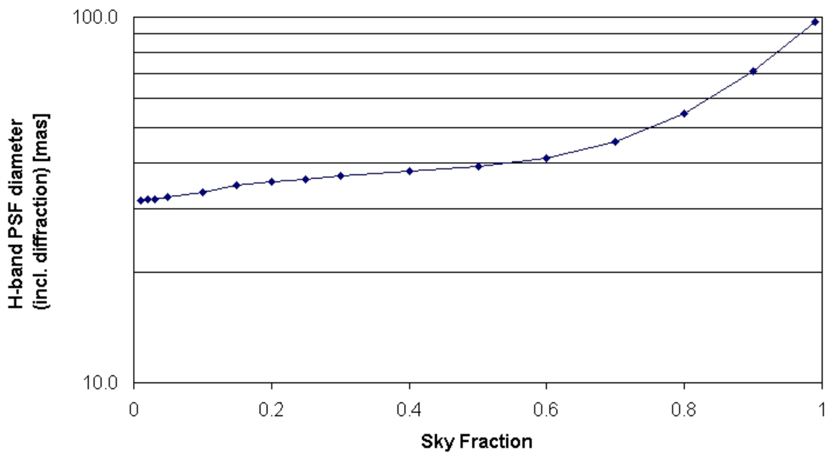

Figure 21 Image width entering a d-IFU versus sky fraction, for actual GOODS-N field and 45° zenith angle.

Figure 22 shows three maps of tip-tilt error, one for each of GOODS-N, GOODS-S and one representative sample region in the COSMOS field. The maps were generated starting from lists of stars in these fields with R magnitudes of 18 or brighter and assuming that the three closest stars to any field position can be used to establish tip-tilt at that field position.

As can be seen from these maps, the worst-case situation, the center of the GOODS-N field, has a tip-tilt error < 30 mas. The COSMOS field has star statistics that are comparable to statistical models of star density (at the Galactic pole in this case) used in the sky coverage analyses throughout this section. In the COSMOS field (and, by implication almost anywhere on the sky) the tip-tilt error is no more than 14 mas and has a median around 8 mas.

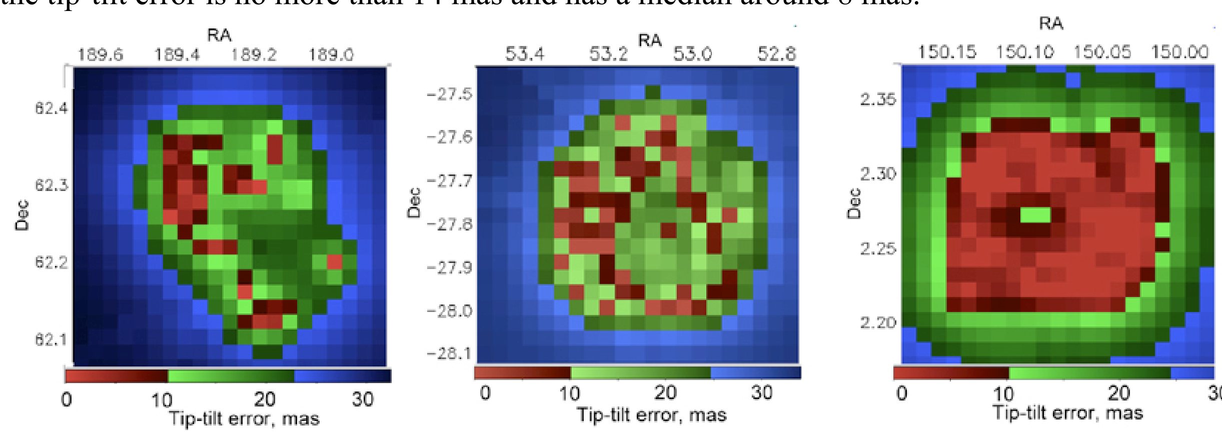

Figure 22: Maps of tip-tilt blurring, for GOODS-North, GOODS-South, and part of the COSMOS deep fields.
A high fraction of these three deep fields is accessible to tomographic observations with NGAO, with less than 25 mas of tip-tilt blurring. GOODS North poses the greatest challenge.

1.4.7 NGAO Instruments

The philosophy for the NGAO instrument compliment is to address the large parameter space offered by NGAO with specialized instruments, and to keep them as simple as possible. By separating wavelength ranges along natural breakpoints based on optical and thermal design considerations and by providing spectroscopy with IFUs we can meet the science needs without requiring multimode instruments. The major exception is a deployable near-IR IFU spectrometer that is of necessity a more complex instrument.

The proposed instrument compliment for NGAO is as follows:

Imaging:
- Visible imager
- Near-IR imager
- Thermal near-IR imager

Spectroscopy:
- Near IR IFU
- Visible IFU
- Deployable near IR IFU

Instruments are designed for Nasmyth platform operation with a single axis of rotation. The proposed arrangement of the AO system optical switchyard will support upward or downward looking instruments and this may be attractive to simplify the instrument design and flexure requirements. Downward looking instruments will be more difficult to access and it appears that the envelope sizes and allowable weights will be more limited as well. Downward looking configurations appear most suited to the imaging instruments, which are simpler and of more modest sizes.

All of the proposed instruments are based either on currently available detector technology or on anticipated evolutionary developments of current technology that we believe will become available within the ~5 year timeframe of NGAO development. Instrument control software and data reduction requirements are expected to be evolutionary developments of current instruments and data reduction tools. It will be important to emphasize close integration with the AO system control software. Features that promote efficient AO observing will be an integral part of the software for every NGAO instrument.

Each of the three major science areas discussed in the proposal has somewhat different instrument priorities. These must be reconciled in order to arrive at a useable priority list. Two important additional inputs to the setting of instrument priorities are the need for appropriate instrumentation for first light commissioning of the AO system, and the relative timescales required for development of the various instruments. Based on the science priorities and these additional considerations we have identified the instrument priorities shown in Table 2.

Table 2: NGAO instrument priorities.

Single object Instruments		**Multi-object Instruments**	
Name	**Priority**	**Name**	**Priority**
Near-IR imager	1	Deployable near-IR IFU	1
Visible imager	2		
Near-IR IFU (OSIRIS?)	3		
Visible IFU	4		
Thermal near-IR imager	5		

The near-IR imager will be the first-light commissioning instrument for NGAO. The deployable near-IR IFU is a high priority instrument, but because of its complexity it will also have the longest development timeline. It is important that the development of the deployable near-IR IFU be started as soon as possible in order for it to arrive as early as possible. However it will likely arrive later than the single object IFUs.

In view of the development timeline for the deployable near-IR IFU the single object near-IR IFU is ranked third because of the clear importance of near-IR spectroscopy. The thermal near-IR imager is a straightforward instrument that could be started at any time, but given the more limited number of science cases that require it, we have ranked it as the lowest priority.

Notional requirements for the imagers are summarized in Table 3.

Table 3: NGAO notional imager requirements.

Instrument	**Wavelength coverage** (μm)	**FOV**	**Sampling**
Visible Imager	0.6 to 1.1	20" x 20"	Nyquist (6 mas)
Near-IR Imager	1.0 to 2.45	20" x 20"	Nyquist (10 mas)
Thermal near-IR Imager	3 to 5.3	25" x 25"	Nyquist (25 mas)

The notional requirements for the deployable near-IR IFU are as follows:

- Wavelength coverage: 1.0 to 2.45 μm
- Multiplex: 6 deployable IFUs (optimum number of units to be studied during design phase)
- Spatial sampling per IFU: 30 x 34 samples
- Sampling scale: 100 mas
- Spectral resolution: R ~4,000
- Spectral sampling: ~2,000 pixels/spectra

The notional requirements for the single object near-IR IFU are as follows:

- Wavelength coverage: 1.0 to 2.45 µm
- IFU Spatial sampling:
  - 80 x 50 samples in a broad band mode
  - 160 x 50 samples in a narrow band mode
- Optional selection of sampling scales: 100 mas, 50 mas, 20 mas
- Spectral resolution: R ~4,000
- Spectral sampling:
  - ~2,000 pixels/spectra in broad band mode
  - ~1,000 pixels/spectra in narrow band mode

We will also study the possibility that OSIRIS might meet many of the needs for this instrument

The notional requirements for the single object visible IFU are as follows:

- Wavelength coverage: 0.6 to 1.1 µm
- IFU Spatial sampling:
  - 60 x 68 samples in a broad band mode
  - 120 x 68 samples in a narrow band mode
- Optional selection of sampling scales: 100 mas, 50 mas, 20 mas
- Spectral resolution: R ~3,000
- Spectral sampling:
  - ~2,000 pixels/spectra in broad band mode
  - ~1,000 pixels/spectra in narrow band mode

1.4.8 NGAO Development Approach

For the development of NGAO we intend to follow the same process used for instrument development at WMKO. The first phase of the project will be a system design phase that will seek to determine the best design approach that meets the scientific and user requirements for the system while balancing complexity, technical risk and cost. The system design phase will establish a discipline integrated engineering plan for the proposed design, understand the technical risks, explore trade-offs, and determine estimates for performance and cost to completion.

A number of trade studies were identified during the first iterative cycle of the system design process. Some of the highest priority studies are as follows:

- Evaluate the performance impact of Rayleigh scatter on NGAO performance and consider various mitigation methods such as a pulsed laser.
- Determine the relative cost versus benefit for alternate optical relay designs.
- Consider the cost/benefits of an adaptive secondary mirror implementation.
- Consider the cost/benefits of a stand-alone tip/tilt mirror as opposed to mounting another necessary optic on the tip/tilt stage.

- Consider cost/benefits of different options for achieving the NGAO science goals in the K through M-bands.
- Determine best way to support Keck-Keck interferometer operations when NGAO is operational.

These and other trade studies will be iterated with the science team so as to optimize the scientific output of the NGAO system and instrument suite.

The key deliverables from the system design phase are a Systems Requirements Document, a Systems Engineering Management Plan (SEMP), a System Design Manual and a System Design Report.

The system requirements document will describe the science and technical requirements for the AO system and instrumentation and show how the technical requirements are related by a flow down process to the science requirements. The system design manual will define the functional requirements for the AO system and instrumentation, describe the design approach for each of the major subsystems and provide a summary of the key technology drivers, technical risks and research and development needs. The system design manual will also present the initial performance and error budgets for the system.

The SEMP will describe the project objectives, major milestones, project organization and project management process. The SEMP will define the project decision process and major decision points, the risk assessment and risk management process, and configuration management plans for hardware, software and documentation.

The System Design Report provides a high level summary of the work done during the system design phase and makes a proposal for the preliminary design phase of the project including a plan for the remainder of the project. This will be developed following a planning sequence based on the system level requirements, and proceeding from a WBS to task identification and description, schedule and budget development and finally a Microsoft Project plan.

1.5 Project Plan, Schedule and Budget

The successful development of NGAO will require the participation of a substantial number of individuals and institutions. The NGAO management structure and institutional participation is expected to evolve during the system design. The eventual structure will be determined by the Observatory Directors/Deputy Director (Armandroff, Lewis, Bolte and Kulkarni) in consultation with key players. The current management structure will continue for the initial system design phase. Peter Wizinowich will continue to coordinate efforts in consultation with Mike Liu and Claire Max of the AOWG and with the active participation of staff from Caltech (Dekany), UC (Gavel) and WMKO (Neyman, Adkins).

At this early point it would be unreasonable to suggest that we have can make any detailed or firm projections for the timeline and costs for the entire project. We have considered the overall timeline and costs at a rough order of magnitude level, and based on this consideration we have identified the milestones shown in Table 4.

Table 4: NGAO Project Milestones.

Year	Month	Milestone
2006	July	Project starts system design phase
2007	June	First major funding secured
2007	September	System Design Review
2008	December	Preliminary Design Review
2010	March	Detailed Design Review
2012	March	AO system and LGS facility pre-ship reviews
2012	December	NGS first light
2013	June	LGS first light
2013	December	Shared risk science operations begin

An initial bottoms-up estimate of the possible costs for the AO and LGS facility portions of the NGAO system is $35M ± $10M, including a 25% contingency. This can be compared with the cost of the somewhat more modest Gemini South MCAO system, budgeted in 2003 at $18M including a single 50 W laser, the current Gemini Planet Imager cost of $19M with a $6M contingency and the more complex TMT NFIRAOS system budgeted at $49M.

Cost estimates for the science instruments have also been developed, primarily by considering the costs of recently completed instruments such as OSIRIS. The total budget to design and implement the first round of the three key science instruments (near-IR and visible imagers plus a near-IR deployable IFU), recommended to take full advantage of the NGAO system, is estimated at $20M ± $4M.

The main goal of planning to date has been to establish a reasonable initial plan and budget for the system design phase. The initial schedule, including labor estimates, for the system design phase activities is shown in Figure 23. The initial cost estimate for the system design phase is $980k. Because of uncertainties in the eventual distribution of effort we consider this initial plan and budget to be reasonable but not firm.

This cost estimate includes 6.4 FTEs of engineer/scientist at WMKO's FY07 $120k/FTE rate, three graduate students and one postdoc to support development of the science requirements, iteration of these requirements during the system design trade studies, and $60k of travel and procurements. The actual labor costs will depend on the individuals and the institutions where this work is performed. We have assumed that Caltech, UC and WMKO will not add overheads since these funds are toward the construction of new instrument capabilities.

1.6 Conclusion

The two essential elements of the scientific leadership of the W. M. Keck Observatory are the creativity and talent of the astronomers who observe here, and the Observatory's ability to offer astronomers world-class facilities and instruments to perform their observations. It is essential that observatories, like other scientific facilities, keep pace with advances in technology. All around us the field of AO is continuing to advance. The present generation of AO at the Observatory is nearly 10 years old and in spite of this we are currently one of the true leaders in the field of astronomical AO. It is a testimony to the skill and dedication of our staff and collaborators that we have persevered in the face of numerous challenges to reach the scientific payoff from our investment.

The success of LGS AO at the Observatory is just a hint of the benefits that will accrue from the continued development of AO. A next generation AO system will be a technically challenging project with significant funding requirements. It would be easy to conclude that the level of risk is too high, and that we should find ways to keep pace with the advancing technology of astronomy in fields other than AO. However, we hope we have shown here that the benefits to science from an ambitious development in AO are tremendous, and these developments are the key to realizing the full potential of the Keck telescopes. Beginning the process of developing AO capability suited to the broad range of high impact scientific problems discussed in this proposal could be the best and most important way to secure the future of the Observatory and our community.

ID	WBS	Task Name	Work
1	**1**	**System Design (SD)**	**17,905 hrs**
2	**1.1**	**SD Phase Management**	**1,685 hrs**
3	1.1.1	SD Plan	40 hrs
4	1.1.2	Management Structure Decision	0 hrs
5	1.1.3	SD Partner Contracts Issued	60 hrs
6	1.1.4	Tracking and Reporting	160 hrs
7	1.1.5	System Design Report	40 hrs
8	1.1.6	Personnel Contingency	1,000 hrs
9	**1.1.7**	**System Design Review**	**385 hrs**
10	1.1.7.1	Reviewers Identified	15 hrs
11	1.1.7.2	Review Package Distributed	0 hrs
12	1.1.7.3	Reviewer Comments Received & Addressed	120 hrs
13	1.1.7.4	System Design Review Prep & Attendance	250 hrs
14	1.1.7.5	System Design Review Meeting	0 hrs
15	**1.2**	**System Requirements**	**5,040 hrs**
16	**1.2.1**	**Science Requirements Updates (rev 1)**	**4,800 hrs**
17	1.2.1.1	Solar System	1,200 hrs
18	1.2.1.2	Galactic	1,200 hrs
19	1.2.1.3	Extragalactic	1,400 hrs
20	1.2.1.4	Technical Support	1,000 hrs
21	1.2.1.5	Revision 1 release	0 hrs
22	1.2.1.6	Revision 2 release	0 hrs
23	1.2.2	Observatory Requirements Updates	40 hrs
24	1.2.3	Technical Requirements Flow Down	120 hrs
25	1.2.4	System Requirements Document (Rev 1)	40 hrs
26	1.2.5	System Requirements Document (Final SD version)	40 hrs
27	**1.3**	**System Design**	**10,200 hrs**
28	**1.3.1**	**Functional Requirements**	**1,000 hrs**
33	**1.3.2**	**Design Approach**	**7,020 hrs**
34	1.3.2.1	System Architecture	500 hrs
35	**1.3.2.2**	**AO System**	**3,200 hrs**
41	**1.3.2.3**	**Laser System**	**1,120 hrs**
49	**1.3.2.4**	**Operations Tools**	**900 hrs**
57	**1.3.2.5**	**Science Instruments**	**1,300 hrs**
66	1.3.3	Technology Drivers Summary	40 hrs
67	**1.3.4**	**Performance Budgets**	**2,000 hrs**
79	1.3.5	Technical Risk Analysis	60 hrs
80	1.3.6	System Design Manual	80 hrs
81	**1.4**	**Systems Engineering Management Plan (SEMP)**	**980 hrs**
82	**1.4.1**	**Project Plan**	**340 hrs**
87	1.4.2	Risk Assessment & Management Plan	40 hrs
88	**1.4.3**	**Preliminary Design Phase Plan**	**160 hrs**
92	**1.4.4**	**Subsystem Testing Plans**	**100 hrs**
97	1.4.5	Integration & Test Plans	100 hrs
98	1.4.6	Configuration Management Plan	80 hrs
99	1.4.7	Project Management Plan	80 hrs
100	1.4.8	SEMP Document	80 hrs

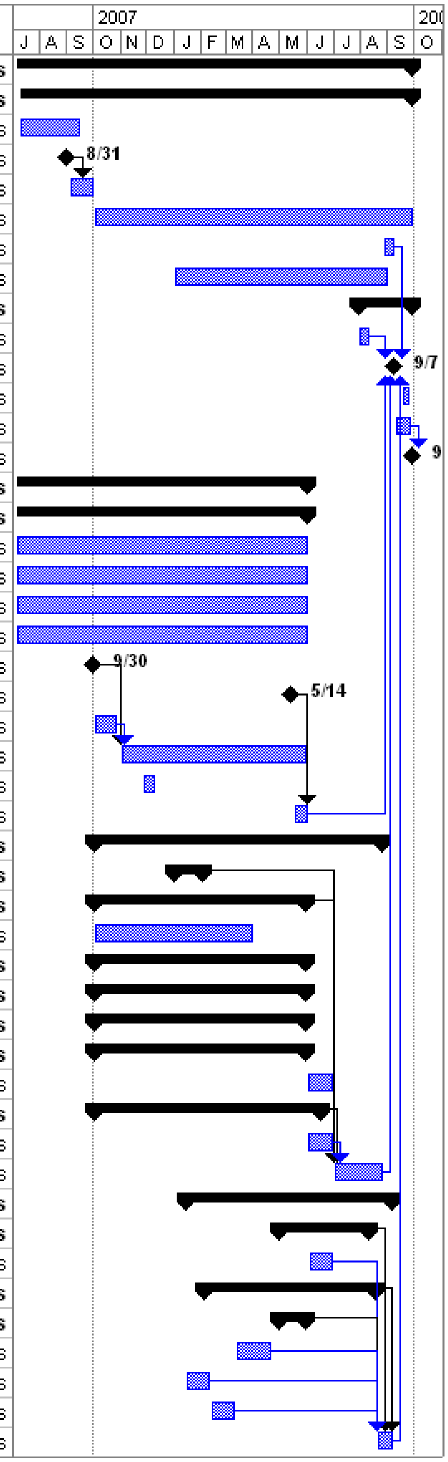

Figure 23: NGAO System Design Phase Project Plan.