W. M. KECK OBSERVATORY

THE NEXT GENERATION ADAPTIVE OPTICS SYSTEM AT THE W. M. KECK OBSERVATORY

A proposal submitted to the Telescope System Instrumentation Program
by the W. M. Keck Observatory

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1. INTRODUCTION

Because of their large apertures, the 10 meter Keck telescopes offer the highest potential sensitivity and angular resolution currently available in the optical and infrared. Unfortunately, without a means to overcome the performance limits imposed by the turbulence of the earth's atmosphere much of the potential of the Keck telescopes would remain unrealized. Adaptive optics (AO) is now an established and fundamental technique for overcoming the effects of atmospheric turbulence. The W. M. Keck Observatory (WMKO) has been among the leaders in the application of AO and laser guide stars and the Observatory's strategic plan recognizes the importance of AO in achieving the full potential of the Keck telescopes by identifying leadership in high angular resolution astronomy as a key long-term goal.

Technology has now advanced to the point that powerful new AO systems and the instrumentation to exploit them are possible. Our consideration of the competitive landscape has shown that there are key opportunities to address clearly differentiable and unique objectives for the future of AO on the Keck telescopes using technologies with the potential to affect second-light AO capabilities on future giant telescopes (e.g. the GSMT). This will be discussed further in §2.4.

In June 2006, a proposal was submitted to the WMKO Science Steering Committee (SSC) to develop a next generation adaptive optics system (NGAO) at the Observatory. This proposal was based on our examination of a broad range of science areas with the objective of identifying the most compelling future science goals of our community and understanding the kind of AO system and instrumentation needed to realize these goals. The proposal was enthusiastically endorsed by the SSC, and in October 2006 we began the system design phase for the AO portion of the NGAO system, with funding from WMKO.

With the introduction of laser guidestar (LGS) AO, we have seen the beginning of wider AO use in our observing community. A key motivation for our desire to develop NGAO is our understanding that with the right level of performance improvements AO can begin to address a much broader range of science programs. This will increase the momentum that has already begun with LGS AO and move high angular resolution astronomy beyond a specialized tool restricted to a narrow range of targets, to a progressively more ubiquitous tool meeting the demands of almost any science program that benefits from high spatial resolution. To accomplish this objective, powerful new NGAO capabilities are being developed that will demonstrate a significant advance in the state of the art for astronomical AO. These include near diffraction-limited performance at infrared wavelengths, significantly increased sky coverage and multiplexing capability, and AO correction into the upper part of the visible spectrum (to 0.7 µm).

NGAO 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 those now being made with the Observatory's current AO systems.

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 benefits 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 or those on other future giant telescopes.

This proposal to TSIP is for the preliminary design phase (i.e. part of TSIP phases A and B) of the AO component of the NGAO system. We propose the exchange of 20 observing nights (starting in semester 2008B) for funding of $2,047,360 over 2 years. The requested start date for this proposal is March 1, 2008. NGAO is being developed by WMKO in collaboration with the University of California and the California Institute of Technology.

The total cost of the NGAO system exceeds by a wide margin the amount requested in this proposal for its preliminary design phase. WMKO plans an extensive private fundraising campaign to supplement the funds available from its annual operating budget and planned future submissions to TSIP. Our proof of principle for such a private-public partnership for NGAO is the $4.98M private donation for MOSFIRE that supplemented

TSIP funds for that important instrument. A strong, accurately-costed preliminary design study is essential for effective private fundraising.

WMKO has exchanged observing time with TSIP since semester 2003A. Keck telescope nights have been the most heavily subscribed observing time offered by the NOAO TAC (for example, note the over subscription factors of 7.88 for Keck I and 8 for Keck II in semester 2005A, as reported in the NOAO Newsletter Volume 81, page 27). The two Keck telescopes are the most scientifically productive in the U.S. observing system. For example, in 2006, 250 refereed publications were published based on data from the Keck telescopes (see http://www2.keck.hawaii.edu/library/2006.htm), the highest number of papers per telescope among US ground-based O/IR telescopes. In addition, TSIP users are reported to be very pleased with the instruments and user support at WMKO according to surveys conducted by TSIP staff. The report of the Second Community Workshop on the Ground-Based O/IR System states "Up to this point, most of the satisfied TSIP observers have used the Keck telescopes, where a good level of support is available."

2. SCIENCE

Since the first publication in 2000 of results from natural guide star (NGS) AO observations at WMKO, more than 175 papers have been published based on NGS and LGS AO observations using the Keck II AO system. LGS AO has become an established observing tool in the WMKO community. The pioneering work of our early adopters in the study of our Solar System and our Galaxy has demonstrated the importance of AO in the future of the Observatory and our community of observers. Demand for AO observing time has led the Observatory to implement an LGS facility on the Keck I telescope and to continue to improve the capability and productivity of the two current AO systems at WMKO.

While continuous improvements to existing facilities have been fruitful and the science achieved to date is impressive, the technical demands of an even greater range of science indicate that a new, next generation AO system would be extremely beneficial. NGAO will have four important characteristics: (1) high Strehl (near diffraction-limited) near-IR performance producing a stable, high contrast point spread function; (2) correction at visible wavelengths to achieve the highest angular resolutions and to access key spectral diagnostics; (3) improved sky coverage; and (4) multiplexing capability over narrow (30") to moderate (2') fields of view, enabling spatially resolved spectroscopy for many objects at once.

2.1. NGAO Science Cases

The development of NGAO is motivated by our understanding, based on more than a year of study; of the range of science that we believe can benefit most from a new AO system. These NGAO science cases illustrate the potential for NGAO to expand into new fields, as well as advances that are possible in the fields where AO is already an established observing tool. In this proposal, we summarize some of the key science cases where NGAO will have significant impact and we stress those cases where the science requirements challenge the parameter space and performance of the AO system.

The simulations described in the science cases are based on residual error budgets that come from performance modeling of the NGAO system for each science case. This has led to an iterative process where the results of the science simulations motivate the development of the NGAO system design, refining the technical requirements and leading to new performance estimates that are then further evaluated in science simulations.

In the following sections, we seek to demonstrate the exciting scientific potential of significantly improved AO system performance and suggest that there are dramatic opportunities for new and important scientific results in extragalactic, Galactic, and Solar System science.

2.1.1. Extragalactic Science

Prior to the availability of LGS AO with its improved sky coverage, AO did not play a significant role in extragalactic science. While the recent progression from natural guide star AO to LGS AO has been a major advance, all current AO systems are still limited in field of view by the isoplanatic angle. Current LGS AO systems use only one laser guide star, limiting the AO performance due to focus anisoplanatism (the "cone effect"). Current LGS systems are limited in sky coverage because of the requirement for a suitable tip-tilt reference star within about 1' of the science object, and today's LGS AO systems are limited to IR wavelengths, making key astrophysical diagnostics at optical wavelengths unobtainable. NGAO will overcome focus anisoplanatism by using multiple laser guide stars and tomographic wavefront reconstruction. The system will improve sky coverage and overcome tilt anisoplanatism by using three AO-corrected near-IR tip-tilt stars.

With these improvements, NGAO will provide good wavefront correction into the R band (~0.7 μm) and the field of view needed for AO-corrected multi-object spatially resolved spectrographic capability. This is a key capability for extragalactic science where unlocking many fundamental questions in galaxy formation and evolution requires large statistical samples, a central methodology that is very challenging for current single-object AO systems. NGAO's multi-object capability will provide the increased sample sizes needed for high-z galaxy studies.

2.1.1.1. Galaxy Assembly and Star Formation History

Within the last decade, the near-IR has become crucial for understanding the early universe and the evolution of galaxies. At $z > 1$, galaxies have shrunk to angular sizes ~1" making seeing-limited observations almost useless at uncovering internal morphologies and kinematics. At the epoch of greatest star formation and AGN activity around $z \sim 2.5$, the traditional optical lines of Hα, OIII and OII are nicely redshifted into the K-, H- and J-bands respectively. The combination of the Keck LGS AO system with OSIRIS spatially resolved infrared spectroscopy is just now starting to dissect some of the brightest galaxies at this epoch. With the gain of ~10 times in sensitivity possible with Keck NGAO (see below), a wealth of new extragalactic science topics can be addressed. Measuring the morphology of star formation, kinematics of proto-disks, internal velocity dispersions and metallicity gradients (e.g. from the NII/Hα ratio) will allow us to characterize the early life of normal galaxies. The cosmic evolution of the quasar population appears to be similar to that inferred for the global star-formation history of the universe; hence the redshift range from 1.5 to 2.5 is also crucial for understanding how the AGN phenomenon is related to galaxy evolution.

Studies of the rate at which the global stellar mass density changes over time indicate that $1 < z < 2.5$ is a critical era of rapid growth for galaxies in this range of redshift (Dickinson et al. 2003). At $2 < z < 3$ the rate of mergers between major galaxies appears to peak (Conselice et al. 2003), and studies of star formation rates at $z \sim 2$ (Erb et al. 2006) indicate that the most massive galaxies at this redshift have nearly completed their growth, while the star forming rate declines more slowly in less massive galaxies. The properties of these galaxies such as star formation rate, stellar mass, gaseous outflow properties, etc. have been studied in detail (e.g. Steidel et al. 2004, Papovich et al. 2006, Reddy et al. 2006 and references therein) but little is known about their internal kinematics or small-scale structure, particularly with regard to the mode of dynamical support or distribution of star formation.

Previous observations with slit spectrographs (e.g. Erb et al. 2004, Weiner et al. 2006) and seeing-limited integral field spectrographs (Flores et al. 2006) suggest that kinematics is frequently inconsistent with simple equilibrium disk models. However, these studies were too constrained by slit misalignment, spatial resolution, and atmospheric seeing to be conclusive. It is therefore unknown whether the majority of star formation during this epoch is due to rapid nuclear starbursts driven by major merging of gas-rich protogalactic fragments, to circumnuclear starbursts caused by bar-mode or other gravitational instabilities, or to piecemeal consumption of gas reservoirs by overdense star forming regions in stable rotationally-supported structures.

The study of high-redshift galaxies is a powerful driver for multiplexed observations, for example via deployable integral field unit (IFU) spectrographs. Given the areal densities of 1 to 10 targets per square arc minute on the sky (depending on the target selection criteria, Table 1), multiplexing using multi-conjugate AO (MCAO) or multi-object AO (MOAO) systems would be a major gain. In order to take best advantage of the high areal densities of targets, it is desirable to be able to deploy of order 6 to 12 AO-corrected IFUs over a ~5 square arc minute field of view.

Figure 1 from our simulations, shows a factor of 3 to 6 improvement in signal to noise ratio (SNR) using an IFU spectrograph with NGAO, compared with the current OSIRIS IFU spectrograph and the current LGS AO system. For background-limited measurements, this would yield exposure-time reduction factors of 9 to 36. Multiple IFUs will further multiply the efficiency. Thus, our nominal 6 head deployable IFU spectrograph with MOAO would yield a dramatic total gain of a factor of 50 to 200 in the completion rate for survey-level programs, relative to the current LGS AO OSIRIS system. This is a major advance in the potential of AO systems for deep spectroscopic surveys of the distant universe.

Type of Object	~Density per arc minute^2	Reference
SCUBA sub-mm galaxies to 8 mJy	0.1	Scott et al. 2002
Old and red galaxies with 0.85 < z < 2.5 and R < 24.50	2	Yamada et al. 2005; van Dokkum et al. 2006
Mergers with emission lines in JHK windows & R < 24	2-5	Conselice et al. 2003
Field galaxies w/ emission lines in JHK windows 0.8 < z < 2.2 & R < 25	> 10	Steidel et al. 2004; Coil et al. 2004
Center of distant rich cluster of galaxies at z > 0.8	> 20	van Dokkum et al. 2000
All galaxies K < 23	> 40	Minowa et al. 2005

Table 1: Space densities of various categories of extragalactic targets

Based on the numerical simulations of Law et al. (2006) and the observed performance of the OSIRIS spectrograph, we anticipate that typical observations (assuming the predicted wavefront error of ~170 nm from the NGAO system) would last 1 to 2 hours per set of targets (for bright star-forming galaxies at redshift z ~ 2) permitting a sample of approximately 25 targets in a given night of dedicated observing. In addition, our simulations show an important gain in information regarding the internal structure of high-z galaxies, as shown in Figure 2. More than 10 times as many pixels have SNRs > 10 with NGAO than with current LGS AO, with the result that a velocity map can be extracted over 3 times more area.

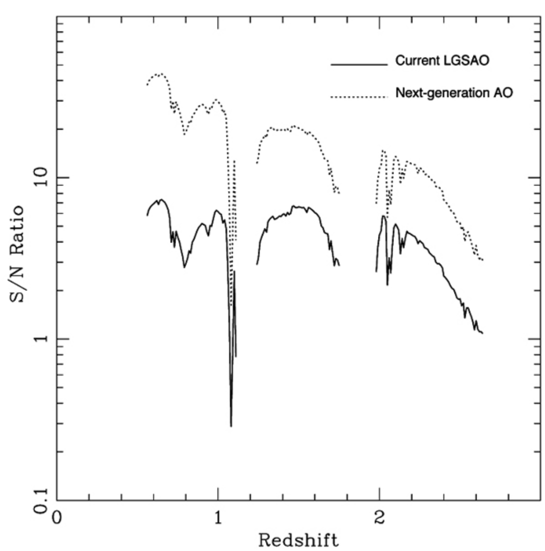


Figure 1: Predicted SNR for NGAO multi-object integral field spectroscopy
This graph shows the predicted SNR for each head of a deployable integral field spectrograph, for NGAO (upper curve), and today's OSIRIS with LGS AO (bottom curve). Over the redshift range 0.6 to 2.3, NGAO shows a factor of 3 to 6 improvement in SNR. Here we have assumed spatial sampling at 0.1" and the improved thermal background planned for NGAO.

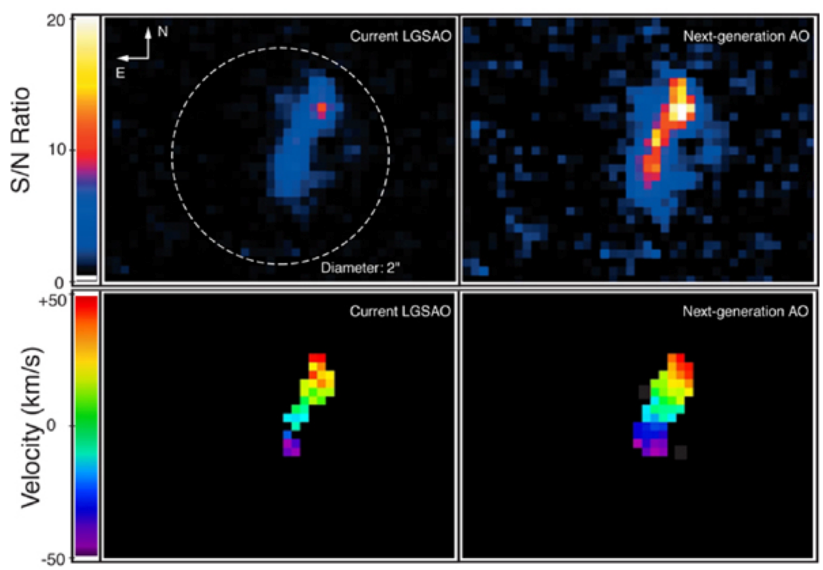


Figure 2: Computer simulation of imaging and spectroscopy of the z ~ 2 galaxy BX 1332 (from the catalog of Erb et al. 2004)
NGAO results in a 3x improvement in SNR for the same exposure time, enabling the study of galaxy morphology for surveys in practical amounts of telescope time. NGAO also allows extraction of a velocity map over 3x more area within the galaxy than the current LGS AO system. Spatial sampling of 0.1" is assumed, and for the velocity maps, only pixels within 3σ of the mean SNR are shown.

2.1.1.2. Strong Gravitational Lensing

Massive clusters and galaxies produce a local perturbation of the Robertson-Walker metric that distorts our view of background objects. This gravitational lensing is achromatic and preserves surface brightness. If the deflector is dense enough and the impact parameter is small enough, multiple distorted images of the background source are seen. This regime is called strong gravitational lensing. Strong lensing is extremely useful for the study of the high redshift universe for two reasons: i) astrometry of the lens configuration depends on the mass distribution of the deflector and on angular size distances, and thus can be used to "weigh" galaxies/clusters, to determine structure of dark matter halos, and to measure cosmography; ii) the background source is highly magnified in apparent size and luminosity, so that lenses act as natural gravitational telescopes: magnification is significant, factors of 10 to 25 in luminosity.

Precision astrometry is key for gravitational lensing. So far, the Hubble Space Telescope has been the unchallenged leader in this area. However, LGS AO has the potential to change the field. The Keck telescope's 10-m aperture can deliver a factor of 4 improvement in angular resolution over HST, if high Strehl ratios can be achieved with NGAO. Further, coupling AO with integral field spectrographs will open the way for high spatial resolution studies of the dynamics and chemistry of high z galaxies, and for detection and spectroscopy of the first galaxies and sources of reionization at z > 7 to 10. As illustrated by the simulations shown in Figure 3, the Keck telescope with NGAO is better than HST for these purposes and will dominate the subject after the demise of HST.

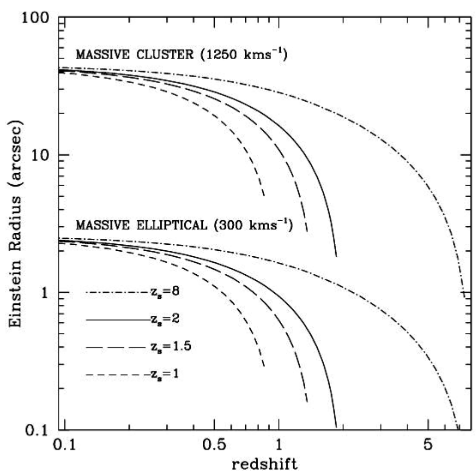


Figure 3: Typical angular scales of cluster-scale lensing and galaxy-scale lensing
Curves show the size of Einstein radius for lensing by a massive cluster (velocity dispersion 1250 km/s) and a massive elliptical galaxy (300 km/s) as a function of deflector redshift. A field of view of 3" to 4" is well matched to galaxy-size lensing, while a field of 1' to 2' is well matched to cluster-scale lensing.

It is useful to separate two regimes: cluster/group lensing and galaxy size lensing. The angular size is set by the Einstein radius, which scales as velocity dispersion squared. The typical galaxies will have Einstein radii of order 1", while massive clusters in the same redshift range will have Einstein radii of order 30", as shown in Figure 3. The current Keck LGS AO system has recently demonstrated the feasibility of deducing properties of high-z galaxies for galaxy-scale lensing using the OSIRIS IFU spectrograph as shown in Figure 4 (Marshall et al. 2007). This figure shows the stars used in the PSF modeling; the Keck K' image has resolution comparable to that of the NICMOS F1690W (approx. H band) image.

The main science goals for the study of galaxy scale lensing are:

- Mass distribution of (mostly early-type) deflector galaxies. What is the mass profile of dark matter halos? What is the fraction of dark matter as a function of galaxy radius, redshift, and mass? Do galaxy-size halos have dark matter substructure?
- Morphology, resolved kinematics, and star formation history/chemistry of faint spiral irregular galaxies. Galaxies can be super-resolved by exploiting lensing magnification. Using NGAO + lensing, the effective diffraction limit in the source plane will typically be ~0.005". This means that galaxies at z = 2 (1.7 Gpc) can be studied with the same detail as a galaxy in the Virgo cluster (17 Mpc) in 0.5" seeing.
- Cosmology through time-delays. If relative photometric precision of a few % can be achieved across the field, monitoring of variable lensed sources such as AGN can be used to determine cosmological parameters. Effectively, each time delay acts as a standard rod. For every system, angular size distances can be obtained with 10-15% precision and therefore there are real prospects of determining

the Hubble Constant to 5% precision if a sample of a few dozen time-delays can be obtained. NGAO would be exceptionally good at this since one needs to do photometry of sources separated by less than 1'.

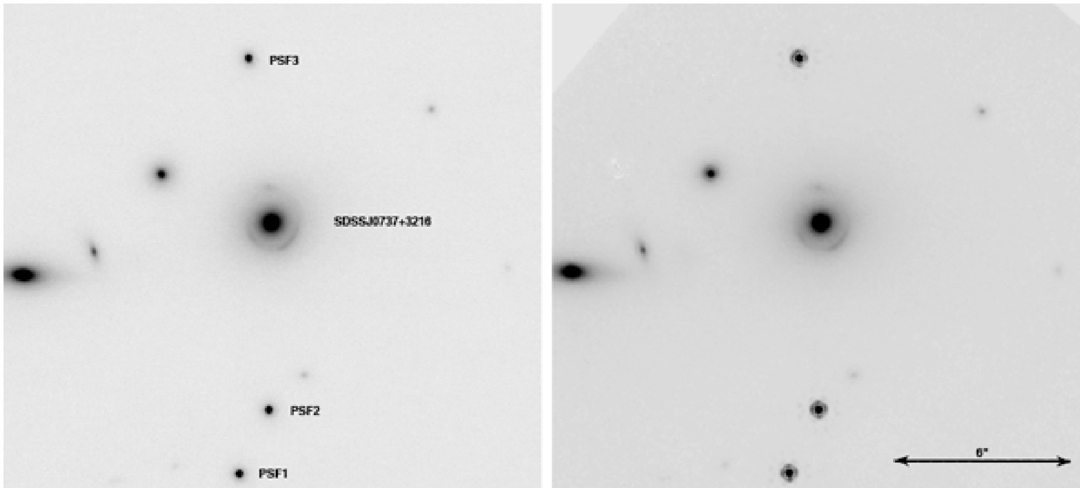


Figure 4: NIRC2 with LGS AO in K' band (left) and HST NICMOS F160W band (right) images of SDSSJ0737+3216

Galaxy-size lenses are rare on the sky; their density is of order 10 per square degree (depending on depth and resolution). NGAO will not be a good instrument to search for lenses, but by the time NGAO is available hundreds of lenses will have been discovered with current technology (e.g. SLACS, Haggles, CFHT Legacy Survey). Thousands of lenses are expected to be discovered by surveys such as DEEP2, z-Cosmos, PANStarrs and LSST. The scientific exploitation of these samples will require high resolution imaging that only NGAO can provide. Analyzing a large number of objects is vital for the applications listed above. For example, to detect substructure satellites must be close to the critical sight lines, which will happen only in a fraction of cases. To beat down small number statistics, hundreds of lenses are needed.

2.1.2. Galactic Science

Galactic science has reaped rewards from each generation of AO, both NGS AO and current single-LGS AO have made numerous significant contributions. However, NGAO's near diffraction-limited performance in the near-IR opens a new realm for measurements with high contrast and precision. NGAO optical imaging will produce the highest angular resolution images from any filled-aperture telescope.

2.1.2.1. Imaging and Characterization of Extrasolar Planets around Nearby Low Mass Stars

Understanding the formation of stars and planets is a key area of Galactic science. There is a well-established timeline for the evolution of these objects: from the collapse of their natal molecular cloud 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 conceptual paradigm remain to be verified, the timescales are not well understood, physical theories are ill constrained, and the diversity of the outcomes is unknown.

The unique combination of high-contrast near-IR imaging (Strehl ratios of 80-90%) and large sky coverage delivered by NGAO (because it will use AO-corrected tip-tilt stars) 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).

NGAO's ability to observe low-mass stars will strongly distinguish it from direct imaging NGS searches planned for other large ground based telescopes (GPI at Gemini, SPHERE at ESO). By number, low-mass stars (< ~0.5 M_{Sun}) and brown dwarfs dominate any volume-limited sample; these objects may represent the most common hosts of planetary systems. Such cool, optically faint targets will be unobservable with specialized extreme AO systems because their parent stars are not bright enough to provide a high-order wavefront reference. However, thousands of cool stars in the solar neighborhood can be targeted by NGAO.

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 otherwise essentially inaccessible to spectroscopy. Figure 5 summarizes the parameter space explored by NGAO and extreme AO such as the Gemini Planet Imager. The complementarity of the two systems is important, and key part of understanding the planet formation process is establishing the mass and separation distribution of planets around a wide range of stellar hosts.

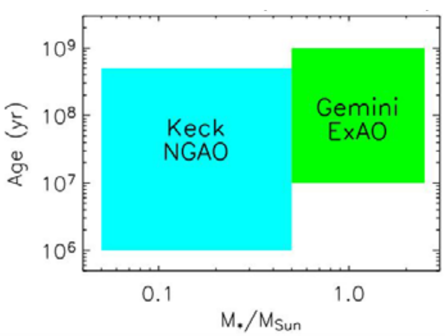


Figure 5: Schematic illustration of the parameter space of NGAO and the Gemini Planet Imager for direct imaging of extrasolar planets.

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. Indeed, the first bona fide L and T dwarfs were discovered as companions to low-mass stars (Becklin & Zuckerman 1988, Nakajima et al. 1995). Thus, searching around low-mass stars is an appealing avenue for planet detection and characterization. Given that low-mass stars are so much more abundant than higher mass stars, they may constitute the most common hosts of planetary systems. Figure 6 shows the simulated direct imaging performance of NGAO for an 8σ detection threshold.

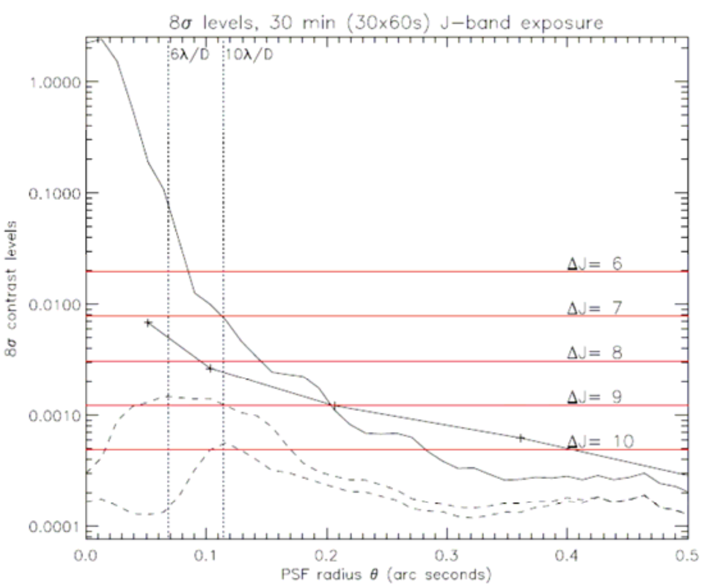


Figure 6: Simulated NGAO performance for direct imaging of planets around low-mass stars.
Red lines show the 8σ contrast levels for various apparent J magnitude differences. Dashed lines indicate the normalized contrast (scaled by 8x) for 6λ/D (upper dashed line) and 10λ/D (lower dashed line) coronagraph occulting spots, assuming 170 nm residual wavefront error, typical near-IR detector performance and a modest amount of speckle suppression. Solid line show scaled, normalized contrast over the PSF without the occulting spot. The line with the + symbols shows the contrast predicted by a simple analytical tool. Source: Keck Adaptive Optics Note 497.

The apparent magnitude differences (Δm) between primary and secondary for a 5 σ confidence level as a function of separation, distance and companion mass for various target samples are shown in Table 2.

Distance	Companion mass	Angular separation	Δm	Notes
20 to 30 pc	2 $M_{jupiter}$	0.2"	ΔJ = 10	Old field brown dwarfs
80 pc	1 $M_{jupiter}$	0.1"	ΔJ = 8.5	Young (< 100 M year) field brown dwarfs and low mass stars
	1 $M_{jupiter}$	0.2"	ΔJ = 11	
	1 $M_{jupiter}$	0.1"	ΔJ = 11	
100 to 150 pc	1 $M_{jupiter}$	0.07"	ΔJ = 13.5	Solar type stars, 1Msun primary mass

Table 2: Required delta magnitude sensitivities for exoplanet detection

Spectroscopic follow-up of the coldest companions will be an important path in characterizing the atmospheres of objects in the planetary domain. Strong water and methane molecular absorption features provide diagnostics of temperature and surface gravity at modest (R~100) spectral resolution. Below ~500 K, water clouds are expected to form and may mark the onset of a new spectral class, "Y dwarfs". Such objects represent the missing link between T dwarfs and Jupiter, but are probably too faint and rare to be detected as free-floating objects in shallow all-sky surveys such as 2MASS and SDSS. Furthermore, the coolest/lowest mass stars may not exist as free-floating objects if there is a low-mass cutoff to the initial mass function of the star formation process, e.g., from opacity-limited fragmentation of molecular clouds (minimum mass ~5 to 10 $M_{Jupiter}$; Silk 1977). Even cooler/lower mass objects might only form via fragmentation, akin to the formation of binary stars, and may only be found as companions.

2.1.2.2. 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 AO imaging of debris disks (through light scattered from circumstellar dust) has been restricted to a handful of the brightest, nearest, edge-on disks. Scattered light studies are better performed at shorter wavelengths, where the lower sky brightness and favorable dust scattering properties lead to optimal contrast between parent star and 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. Observations of disk substructure are a very promising method to detect the presence of Neptune-class planets, otherwise undetectable by direct imaging or radial velocity surveys.

Debris disk surveys by NGAO at near-IR wavelengths will have lower angular resolution but higher PSF stability than those in visible light. 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 (age 120 My), 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.

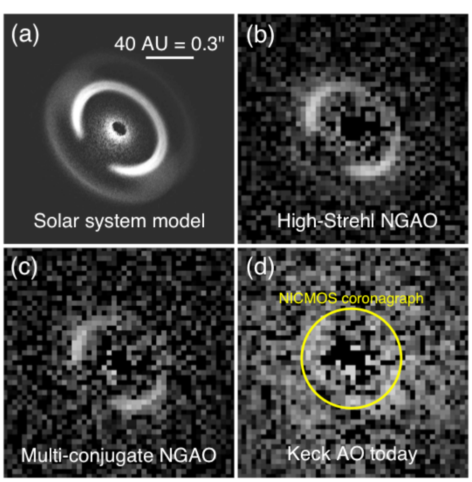


Figure 7: Simulated H-band images of a massive Kuiper belt analog around a solar-type star.
The assumed Strehl ratios of the simulated images are 82% (panel b), 47% (panel c), and 28% (panel d). The AO images are all shown with the same linear grayscale. The size of the smallest coronagraph available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

2.1.2.3. Measurements of General Relativity Effects in the Galactic Center

The proximity of our Galaxy's center presents a unique opportunity to study a massive black hole (BH) and its environs at much higher spatial resolution than for any other galaxy. In the last decade, near-IR observations with astrometric precision of < 1 mas and radial velocity precision of 20 km/s have enabled measurement of orbital motions for several stars near the Galactic Center (GC), revealing a central dark mass of 3.7 x 10^6 M_{sun} (Ghez et al. 2003, Ghez et al. 2005; Schodel et al. 2002; Schodel et al. 2003). Radio VLBA observations have now resolved the central object Sag A* to within several multiples of the event horizon, indicating that the central mass is confined to a radius smaller than 1 AU (Shen et al. 2005). These observations provide the most definitive evidence to date for the existence of massive BHs in the centers of galaxies. The orbital motions now provide the most accurate measurement of the GC distance R_0, constraining it to within a few percent (Eisenhauer et al. 2003).

Due to the crowded stellar environment at the GC and strong line-of-sight optical absorption, tracking stellar orbits requires the high angular resolution, near-IR imaging capabilities of adaptive optics on telescopes with large primary mirrors. Though current orbital reconstructions are consistent with pure Keplerian motion, with Keck NGAO we will be able to detect deviations from Keplerian motion due to a variety of effects. These will provide a unique laboratory for probing the dynamics of galactic nuclei, the properties of exotic dark matter, and the mass function of stellar-mass black holes, and the first tests of general relativity in the high mass, strong gravity, regime. Keck NGAO will measure these non-Keplerian motions to precisions that will not be greatly surpassed even in the era of extremely large (~30m) telescopes.

Of the theories describing the four fundamental forces of nature, the theory that describes gravity, general relativity (GR), is the least tested. In particular, GR has not been tested in the strong field limit, on the mass scale of supermassive BHs. The highly eccentric 15 yr orbit of the star S0-2 brings it within 100 AU of the central BH, corresponding to ~1000 times the BH's Schwarzschild radius (event horizon). Studying the pericenter passage of S0-2 and the other high eccentricity stars therefore offers an opportunity to test GR in the strong gravity regime.

With NGAO, stellar orbits can be monitored with sufficient precision to enable measurement of post-Newtonian GR effects associated with the BH: relativistic prograde precession, extended mass within the stellar orbits, and frame dragging due to BH spin. Astrometric precision required for these measurements is illustrated in Figure 8. Low-order general relativity and extended matter effects are detectable at the >5σ level with astrometric precision of ~200 μas, while 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 predict that astrometric precision on the order of 100 μas will be obtained with NGAO. As Figure 8 illustrates, GR prograde precession can be measured even for single orbits of known stars (e.g., S0-2, K=14.1) for astrometric precision of ~ 100 μas and radial velocity precision of 10 km/s.

In summary, NGAO will bring the following important improvements to measurements at the Galactic Center:

1. Current measurements are strongly confusion limited, because the Galactic Center is a very crowded field. High Strehl at K-band will improve contrast and reduce confusion, improving both photometric and astrometric accuracy because the previously undetected faint star population will cause less of a bias in the positions and magnitudes of brighter stars.
2. Higher K band Strehl will allow detection of new stars, some of which may pass close enough to the black hole to improve the measurement accuracy and precision of general relativistic effects.
3. The accuracy of current radial-velocity measurements is limited by the attainable SNR. NGAO's higher Strehl and lower sky background at K band will materially improve the radial-velocity contribution to orbit determination

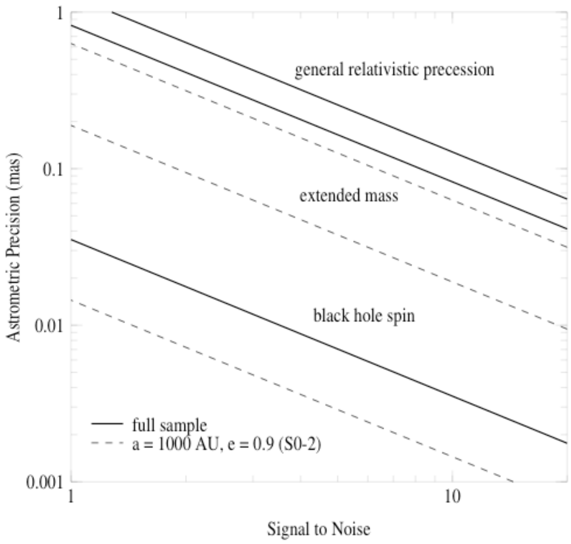


Figure 8: Required astrometric precision for detecting GR effects in the Galactic Center region. *Shown from top to bottom are the astrometric precisions required to detect general relativistic effects associated with relativistic prograde precession, due to extended mass within the stellar orbits, and frame-dragging effects due to the spin of the BH (based on Weinberg et al. 2005). This graph assumes a 10-year observational baseline, with 10 observed epochs per year.*

2.1.3. Solar System Science

2.1.3.1. Multiplicity, Size, and Shape of Minor Planets

Study of remnants from the Solar System formation provides insight into the conditions that existed at the time of solar system formation. Such information has been locked into the orbits and properties of asteroids and Kuiper Belt objects. The AO study of binary (and multiple) minor planets is one key path to revealing these insights, specifically by studying their kinematics and geological properties. There are no space missions currently planned to study these binaries.

High angular resolution studies are needed of large samples of binary asteroids to understand how their enormous present-day diversity arose from their formation conditions and subsequent physical evolution, through processes such as disruption and re-accretion, fragmentation, ejecta capture, and fission.

Specifically one can study formation and interiors of minor planets by accurate estimates of the size and shape of minor planets and their companions; mass, density, and distribution of interior material by precise determination of the orbital parameters of moonlet satellites; and chemical composition and age, by combining high angular resolution with spectroscopic analysis.

2.1.3.1.1. Size and Shape

Spatially resolved imaging of large asteroids is critical to statistically constrain large collisions throughout the Main Belt. Observation of the 15 or 20 largest asteroids would provide the statistics necessary to put strong constraints on the frequency of major collisions. We calculate that 20 Main Belt asteroids will be sufficiently resolved with NGAO in R-band (33 in V-band) to obtain mapping comparable to that already done for 4 Vesta. Table 3 summarizes the number of asteroids resolvable from visible to near-IR, by domain and population. Thanks to NGAO’s high angular resolution in V and R bands, ~800 main-belt asteroids can be resolved and their shape determined with a precision of better than 7%. With the current AO system ~100 asteroids, located only in the Main Belt, can be resolved. Determination of the size and shape of even a few Trojan asteroids can help estimate their albedo. The large number of resolvable Near Earth Objects is due to their close approach to Earth.

2.1.3.1.2. Orbits of Multiple Asteroidal Systems

One of the main limitations of AO observations for binary asteroid searches and orbit characterization has been the limited number of asteroids observable, due to the magnitude limit on the NGS wavefront sensor. With NGAO, ~10% of the known main-belt population can be searched, corresponding to the potential discovery of 1000 multiple systems assuming the current multiplicity rate of 6% - 15%. This is a lower limit on the detection rate of new moonlets, because the NGAO system will provide a more stable correction than current Keck LGS AO, and the seeing halo will be significantly reduced.

Orbital type	Total number	V < 15	15 < V < 16	16 < V < 17	17 < V < 18
Near Earth	3923	1666	583	622	521
Main Belt	318474	4149	9859	30246	88049
Trojan	1997	13	44	108	273
Centaur	80	1	1	2	2
TNO	1010	1	2	0	2
Other	3244	140	289	638	870

Table 3: Number of asteroids resolvable with NGAO

Numbers are given for various wavelength ranges and populations, assuming on-axis observations. Populations are by brightness for both numbered and unnumbered asteroids.

At the time of this writing, the orbits of ~15 visual binary asteroid systems are known and display considerable diversity. To better understand their differences, a study would focus on ~100 new binary systems in the Main Belt discovered by light-curves or snap shot programs on HST or previous AO systems. The increase of known orbits by an order of magnitude will help us understand how asteroids formed as members of a collisional family as a function of their distance to the Sun, their size, and shape.

To illustrate the gain in quality expected with NGAO, we generated a set of simulated images of the triple asteroid system 87 Sylvia. The binary nature of this asteroid was discovered in 2001 using the Keck II telescope's NGS AO system. Marchis et al. (2005) announced recently the discovery of second moonlet. The system is composed of a D = 280 km ellipsoidal primary around which two moons describe a circular and coplanar orbit: "Romulus", the outermost moonlet (D=18 km) at 1356 km (~0.7") and "Remus" (D = 7 km) at 706 km (~0.35"). In the simulation, we artificially added two additional moonlets: "S1/New" (D=3.5 km) located between Romulus and Remus (at 1050 km) and "S2/New" (D=12 km) at 480 km. This system is particularly difficult to observe since the orbits of the moons are nearly edge-on. We blurred the image using the simulated NGAO and Keck NGS AO PSFs and added Poisson and detector noise to reach a S/N of 2000 (corresponding to 1-3 min integration time for a V=12 target). We then estimated whether the moonlets could be detected and their intensity measured by aperture photometry.

Table 4 summarizes the 2-σ detection rate for the pseudo-Sylvia moonlets. Photometry was done using the same technique as for real observations (aperture photometry + fitting/correction of flux lost). Detection rates for NGAO- R band are 100% for all moons. We see very good photometric recovery with this AO system. It should be also emphasized that because the astrometric accuracy is improved, determination of the orbital elements of the moons will also be more accurate.

	Romulus		**Remus**		**S_New1**		**S_New2**	
	Det. rate	Δm	Det. Rate	Δm	Det. Rate	Δm	Det. Rate	Δm
Perfect image	100%	6.6	100%	8.1	100%	6.9	100%	9.6
NIRC2-H	82%	6.4±0.04	70%	8.3±0.3	11%	6.9±0.2	0%	N/A
NGAO-H	100%	7.0±0.1	70%	8.5±0.5	40%	7.1±0.2	0%	N/A
NGAO-R	100%	6.60±0.01	100%	8.3±0.1	100%	6.9±1.1	100%	10.1±0.3

Table 4: Detection rate and photometry on the moons of pseudo-Sylvia

(NGAO total wavefront error = 140 nm)

2.2. NGAO Science-Based Requirements

The science-based requirements for NGAO are aimed at describing the observational performance needed to address each of the NGAO science cases in two broad categories: observations in a specific range of parameter space, and imaging or spectroscopic observations with specific levels of performance or accuracy.

The requirements presented here are not top down directives from the science cases, but instead are the result of iteration between the science and technical teams. Initial AO performance estimates were used to develop simulated observations for specific science cases. The results then provided input to the technical teams, indicating areas where initial performance estimates were not well matched to science requirements. This process has resulted in a practical approach that achieves a good correspondence between proposed NGAO science and the technical capabilities of the NGAO system.

2.2.1. Science Requirements Summary

The NGAO science requirements are summarized in Table 5 and discussed in the following sections.

Requirement	Value(s)	Driving science cases
Parameter space		
Wavelength range	0.7 to 1.0 μm	Galactic science, nearby AGNs, Solar System science
	0.9 to 2.45 μm	All
Sensitivity	See Table 6, R & I band	Galactic science, nearby AGNs, Solar System science
	See Table 6, J, H & K band	All
Wavefront error	140 nm	Solar system: moons of giant planets, multiple asteroids
	170 nm	All
	200 nm	Galactic and extragalactic science
Field of view	~2"	Asteroid companions
	≤ 3"	Moons of giant planets, high-z field galaxies
	5"	Exo-Jupiters, gravitational lensing by galaxies
	≥10"	Galactic Center
	≤ 20"	Debris disks
Performance		
Background	≤ 30% over the unattenuated sky+telescope background (goal: 20%)	Extragalactic science
Contrast	ΔJ=11at 0.2" separation	Exo-Jupiters
	ΔH=5.5 at 0.5" separation	Asteroid companions
	ΔI=7.5 at 0.75"separation	Asteroid companions
Photometric accuracy		
Absolute	≤ 0.05 magnitudes	Moons of giant planets
Relative	≤ 0.05 magnitudes	Asteroid companions
	~0.1 magnitudes	Galactic and extragalactic science cases
Astrometric precision	100 μas	Galactic Center
	500 μas	Exo-Jupiter primary mass determinations
	1.5 mas	Asteroid companion orbit determinations
	10 mas	Exo-Jupiter orbit determinations
Sky coverage	≥ 30% (areal average over all sky)	Extragalactic science
		Galactic science, Kuiper belt objects
Observing modes		
Imaging	Visible	Moons of giant planets, Galactic science
	Visible with coronagraph	Asteroid companions
	Near-IR with coronagraph	Asteroid companions, exo-Jupiters
Spectroscopy	Visible	Asteroid companions (r ~100), Galactic science & nearby AGNs (r ~4,000)
	Near-IR IFU	Asteroid companions, exo-Jupiters (r ~100), Galactic science (r ~4,000)
	Near-IR multi-object deployable IFU	Extragalactic science, 1" x 3" per IFU head, field of regard ≥ 120", r ~4,000

Table 5: NGAO science requirements summary

2.2.2. Parameter Space Requirements

2.2.2.1. Wavelength Range

AO observing in the near-IR is well established, and all of the NGAO science cases require capability in the range from 1.0 µm to 2.45 µm, covering the Y, J, H and K bands. From a technical point of view it turns out that achieving the Strehl goals for near-IR performance (for example >80% at 1.65 µm) lead to useful Strehl performance (~20%) in the I band and a portion of the R band (to 0.7 µm). Our Solar System and Galactic science cases will obtain significant benefit from AO corrected visible wavelength observations in the red end of the visible spectrum (down to at least R band). For extragalactic science, the accessibility of the calcium triplet at ~850 nm is crucial to greatly improved black hole mass measurements in nearby AGNs.

Limitations on K-band sensitivity due to emissivity of the telescope and AO system are well recognized at WMKO. We expect to cool the AO system to achieve improved sensitivity over that offered by the current Keck telescope AO systems. Strategies to further reduce background, such as an adaptive secondary mirror with several thousand actuators, are not currently available and will be too expensive for the scope of the NGAO project. As a result, performance at wavelengths longer than K band is likely to be inferior to other facilities such as JWST, causing NGAO to place a low priority on wavelength coverage beyond ~2.45 µm.

2.2.2.2. Sensitivity

NGAO is expected to provide a significant gain in sensitivity over the current Keck telescope AO systems. This is due to the improved Strehl ratio, and to improved background and transmission. For some science cases such as high-z galaxies, the desired sensitivity is constrained by the duration of reasonable spectroscopic exposures. Science programs concerned with imaging surveys place a premium on achieving background limited observations with shorter integration times. In other science cases such as binary asteroids or companions to low-mass stars, the sensitivity requirement ties directly to limits on detectability or contrast. We have adopted a standard of 5 σ in one hour as the reference point for point source limiting magnitude, with one hour integration times representing a reasonable time for programs such as extragalactic surveys with relatively large numbers of targets. The current performance estimates for NGAO point source limiting magnitude are shown in Table 6.

Filter	Zero-point (magnitudes)	Sky (mag. arcsec^{-2})	Point source limiting magnitude (5σ in 1 hr of integration)		
			140 nm	195nm	330nm
V	27.09	21.3	28.7	27.6	27.6
R	27.10	20.4	29.0	27.1	27.1
I	26.98	19.3	29.0	27.7	26.5
J	25.47	16.1	27.0	26.5	24.4
H	25.51	13.8	25.8	25.6	24.4
K'	24.84	13.5	25.2	25.0	24.4

Table 6: Point source limiting magnitudes for broad band imaging

2.2.2.3. Wavefront Error

The usefulness of many observations can be directly understood as a function of residual wavefront error, with some observations experiencing a graceful degradation of other parameters in the presence of increased wavefront error. For many of these observations this increased wavefront error is amenable to some degree of compensation (for example a reduction in sensitivity may be compensated by longer exposures), while other observations become impractical once wavefront error increases beyond a certain level (this is the case with the precision astrometry needed for some Galactic Center science).

Initial estimates of NGAO system performance based on laser tomography AO resulted in residual wavefront error estimates ranging from ~100 to 200 nm. Based on these initial estimates we adopted three representative values of residual wavefront error for our science case simulations: 140 nm, 170 nm and 200 nm. The science driven requirements for wavefront error given here are therefore derived from testing actual levels of wavefront error in simulated observations, and as such represent the current best understanding of the wavefront error levels acceptable for various NGAO science programs.

2.2.2.4. Field of View

All of the Solar System and Galactic science cases identified for NGAO require modest to narrow fields of view, ranging from 2" to 20" and observing one object at a time. In general, Nyquist or over sampling (2x Nyquist) is desired, leading to a good match with imagers using 4k x 4k detectors in the visible wavelength range and 2k x 2k detectors in the near-IR. For near-IR spectroscopy, single object IFUs with the desired sampling (see §3.2.3) can achieve the required field of view using either a 4k x 4k detector or a mosaic of two 2k x 2k detectors.

High-z galaxy science cases require a multi-object IFU with 6 to 12 heads deployable over at least a 120" field of regard. Each channel requires a 1" x 3" field of view, achievable with a single 2k x 2k detector for each IFU head.

2.2.3. Performance Requirements

2.2.3.1. Background

Control of background flux from the telescope and AO system is essential to maximize the SNR of the observations and to reach the required sensitivity in reasonable integration times. At wavelengths shorter than ~2 μm the background in a well designed optical system free from scattered light is due to night sky emission. For wavelengths > 2 μm, background flux due to thermal emission from the telescope and AO system becomes very significant. Our studies of the impact of background on sensitivity for near-IR observations have resulted in a requirement that the AO system should not increase the unattenuated background from the sky+telescope by more than 30%, with a goal of 20%.

2.2.3.2. Contrast

Particular NGAO science cases require the imaging and spectroscopic characterization of a faint secondary object in close (< 1") proximity to a much brighter primary object. These are further divided into programs where a relatively high performance coronagraph is used to suppress light from the brighter object (usually a star) and programs where the central object is itself resolved and hence not suited to suppression with a mask.

Contrast requirements are stated in terms of angular separation and apparent magnitude difference (Δm) between the primary and secondary, assuming a confidence level for the detection of the secondary object. For the extrasolar planet case, 5σ detection of a Jupiter mass planet with ΔJ=11at 0.2" separation would allow detection of companions for a range of young (<100 My) field brown dwarfs and low mass stars out to 80 pc. For the asteroid companion case, requirements are for 8σ detection at ΔH=5.5 at 0.5" separation and ΔI=7.5 at 0.75"separation which are expected to allow detection of potential companions for approximately 10% of the main belt asteroid population.

2.2.3.3. Photometric Accuracy

Requirements for photometry are part of all of the NGAO science cases, with varying requirements for accuracy in both relative and absolute photometry. For Solar System science synoptic observations of moons such as Io and the study of asteroid companions require absolute photometry with an accuracy of ≤ 0.05 magnitudes. For the Galactic and extragalactic science cases relative photometry to ~0.1 magnitudes is required. This is somewhat better than what has already been achieved (0.14 magnitudes) with LGS AO on the Keck II telescope for an H = 23.9 supernova at z ~ 1.3 (Melbourne et al. 2007).

2.2.3.4. Astrometric Precision

The most demanding applications for astrometric precision and accuracy come from the study of the Galactic Center. Astrometric accuracy of 100 μas (micro-arc seconds) is required for reliable detection of general relativity effects associated with relativistic prograde precession of stellar orbits about the central black hole. Accuracies better than 200 μas are currently achieved with today's laser guide star AO system used on the Galactic Center (where more than 1000 stars are used for a joint solution).

For the determination of the orbits of exo-Jupiters around low mass stars, the measurement of proper motions to the level of 0.1" per year require astrometric accuracy of 10 mas (milli-arc seconds). Astrometric accuracies of 500 μas allow determination of primary mass to the 10% level. We note that relative astrometry of 1 to 5 mas (depending on the target) is achieved with today's Keck AO systems. For determination of the orbits of asteroid companions, astrometric accuracies of 1.5 mas are required.

2.2.3.5. Sky Coverage

Each NGAO science case has requirements for access to some number of targets under a set of specified conditions, driven by either the abundance of objects or the need to gather statistics from a large number of targets. For the science cases that will rely on LGS AO tomography, the availability of AO corrected tip-tilt stars of sufficient magnitude is the main factor in determining sky coverage. Our assessment of the required numbers of targets for the extragalactic science case indicates that sky coverage fractions of 30% (areal average over the entire sky) are needed. Similar sky coverage fractions are needed for the search for exo-Jupiters and direct imaging studies of debris disks.

2.2.4. Observing Modes

The NGAO science cases require various combinations of imaging and spectroscopic observations. Both visible and near-IR imagers are required, each with at least Nyquist sampling and provisions for conventional coronagraphs. For the highest contrast applications a coronagraph optimized for narrow inner working angles using techniques such as non-redundant aperture masking is also being considered. Conventional slit spectroscopy or IFU spectroscopy are both possibilities for visible wavelengths, while in the near-IR an IFU for spatially resolved spectroscopy is considered mandatory. The extragalactic science cases drive the need for a multi-object deployable IFU with between 6 and 12 heads.

2.3. The Larger Context for NGAO at W. M. Keck Observatory

The world's other large telescope observatories (Gemini, Subaru, LBT, and ESO) are currently 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 9 shows an estimate of the current and future funding levels for astronomical AO recently complied by J. Frogel of AURA. This estimate does not include an additional ~ $2M per year from the European Union's Opticon program.

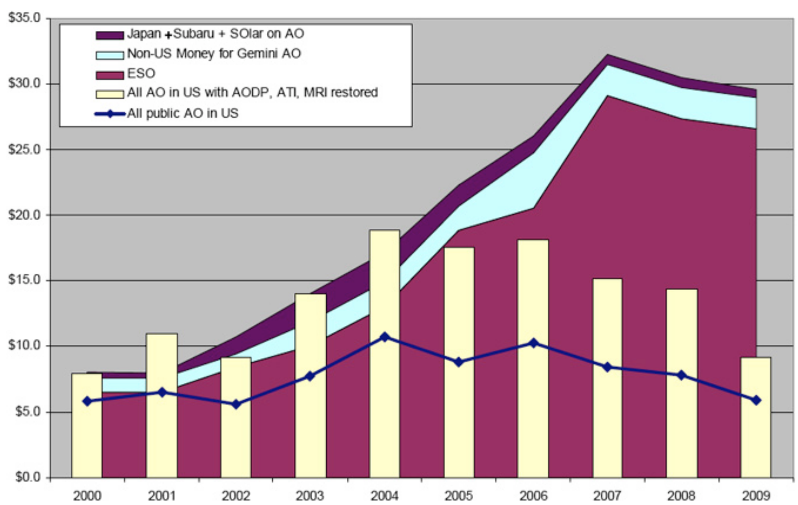


Figure 9: European and US investment in astronomical AO.
Source: J. Frogel, AURA

Quoting from a recent article "Current projections indicate that AO implementation on public and private telescopes in the U.S. will soon seriously lag that on the ESO VLT as measured by funds available. There needs to be a significant infusion of public funds for AO development (through AODP) and for AO implementation (through TSIP) so that, when combined with private funds, the U.S. astronomical community as a whole can take full advantage of AO systems on both public and private telescopes[1]."

[1] Gemini Focus, December 2006, page 82

With the exception of the Gemini South MCAO system, almost 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 projects is directed at general purpose near diffraction-limited (Strehl >75%) performance in the near-IR. Likewise, no large telescopes are currently attempting to extend high-order AO correction to visible wavelengths.

The current direction of AO development at other large telescopes creates a well-defined opportunity to pursue high performance NGAO with the emphasis on diffraction-limited performance over narrow and moderate fields. NGAO will enable science that depends on the precision possible with higher spatial resolution and the sensitivity gains that accompany near diffraction-limited imaging in the near-IR. Achieving this near-IR performance will also give us a system capable of high angular resolution at the red end of the visible wavelength bands. NGAO corrected deployable multi-object IFU capability will be unique.

From a competitive point of view, extending the application of AO into the visible wavelengths will open new territory for high angular resolution astronomy. 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 role for AO at WMKO, even after the construction of much larger telescopes.

2.4. Complementary Capabilities

In the context of the O/IR System, NGAO offers a well-defined set of capabilities that are not duplicated elsewhere. NGAO will supercede the performance of one of the current LGS AO systems at WMKO. In addition, NGAO with its narrower field and higher Strehl will compliment the Gemini South MCAO system, where wide field performance is emphasized in exchange for a more moderate Strehl ratio. With the exception of the Gemini South MCAO system, all of the other second-generation AO projects are directed either at seeing improvements, primarily ground layer AO, or extremely high contrast "planet finding" AO. None is directed at achieving general purpose near diffraction-limited (high Strehl) performance in the near infrared. Likewise, no large telescopes are currently attempting to extend high-order AO correction to visible wavelengths, or to implement multi-object AO-corrected IFUs.

Examination of the 2007B NOAO Proposal Web pages (see also NOAO Newsletter Volume 89, pp. 14 - 18) shows that only WMKO and Gemini provide large-aperture AO capability for the NOAO/TSIP observing community. Yet, the Third Community Workshop on the Ground-Based Optical/Infrared System (Scottsdale, Arizona, November 2006) amply demonstrated community demand for AO imaging and spectroscopy on large aperture telescopes. The scientific issues driving this demand include the physics of star formation, exoplanet detection and characterization, and the formation and evolution of galaxies, particularly at high redshift. In the northern hemisphere, the only large-aperture AO systems available to the broad U.S. community are at Gemini North and WMKO. As discussed elsewhere in this proposal, the Keck NGAO System will be distinguished from the Gemini North AO system by a greater degree of AO correction, a more significant field of regard, extension to visible wavelengths, and the availability of an AO corrected multi-object deployable IFU.

In developing the science requirements for NGAO, we took into account new space based and radio astronomy capabilities in order to define the areas of parameter space for NGAO that will best complement their performance. In some cases, space assets have superior capabilities that NGAO should not attempt to duplicate, and in other cases, there are areas that NGAO should emphasize in order to maximize the complementarity of NGAO observations, continuing the well established synergy between large AO-corrected telescopes in the near-IR and space-based or radio astronomy facilities.

The James Webb Space Telescope (JWST) will have considerably better faint-source sensitivity than NGAO due to its low backgrounds, particularly in the K band. JWST's NIRCAM instrument has diffraction-limited imaging for wavelengths between 2.4 and 5 μm, but not below 2 μm due both to the primary mirror quality specification and to the undersampled pixel scale (0.035") within NIRCAM. Thus NGAO can complement JWST's imaging capabilities with diffraction limited imaging at wavelengths below 2 μm. For spectroscopy, NGAO can complement JWST's NIRSpec multi-object spectrograph in areas that include spectroscopy with spatial resolution better than 0.1", multi-IFU spectroscopy, and slit or IFU spectroscopy near the Keck telescope's diffraction limit at wavelengths from 0.6 to 2 μm. It will be very difficult for NGAO to compete with JWST at wavelengths longer than K band, because JWST will have far lower backgrounds. Even at the long-wavelength end of K band NGAO will not be competitive in sensitivity with JWST's NIRSpec.

The Atacama Large Millimeter Array (ALMA) will excel at the study of chemical evolution in star-forming regions at z ~ 3, dust-gas interactions, molecules surrounding stars, and molecular clouds. With its high sensitivity it will detect redshifted continuum dust emission out to z = 10. ALMA's spatial resolution in the mm and sub-mm bands will be competitive with Keck's diffraction limit at wavelengths of 0.6 to 2.4 μm. ALMA will be observing regions that are colder and denser than can be seen in the visible or near infrared at WMKO. However, NGAO observations of H_2 and atomic hydrogen emission lines in the H- and K-bands will complement ALMA by characterizing the warmer outer regions of molecular clouds and circumstellar disks. ALMA images and spectra of debris disks will complement the higher spatial resolution NGAO images at shorter wavelengths. In addition, ALMA images of extragalactic objects will be an extraordinarily well-matched complement to NGAO imaging and spectroscopy.

3. TECHNICAL

At the time of this proposal, the technical development of the AO portion of the NGAO system is at approximately the mid-point in an 18-month system design phase.

The objective of the system design phase is to establish a design approach that meets the scientific and user requirements established for the system. To do this we have initiated an iterative process that starts with the high level scientific and user requirements, proposes a design concept and then evaluates the ability of the concept to meet the requirements. Throughout this process we have performed trade studies in order to guide the system design process and select the best design concepts and later guide the allocation of function to subsystems and components. When the design approach emerges that appears best able to meet the science requirements an architecture is established that defines the required subsystems or components. The same iterative process is then applied to each subsystem until the design is understood well enough to allow writing the system's requirements for performance, implementation and design. These system requirements are derived or "flowed down" from the scientific and user requirements.

NGAO has now (as of August 2007) reached the point where a design approach has emerged, and the overall architecture and allocation of function to subsystems has been established. We are now refining the system requirements and beginning the development of functional requirements for those subsystems.

3.1. AO System Overview

All of the NGAO science cases discussed in §2.1 require essentially diffraction limited performance (Strehl > 0.6) in the near-IR. A number of Solar System and Galactic science cases have requirements for at least modest Strehl in the visible wavelengths. All of the science cases also require high sensitivity with most of the targets of interest being too faint to use as references for wavefront sensing in the AO system. This high Strehl, faint object performance is required with reasonable (≥ 30%) sky coverage.

The requirements for sky coverage and high sensitivity are both met by using a laser of 589 nm wavelength to illuminate the mesospheric sodium layer, producing an artificial "laser" guide star (LGS) for AO wavefront sensing. Achieving the desired level of Strehl performance leads directly to a requirement for an AO system that can overcome the effect of focus anisoplanatism (the "cone effect"), a requirement that is met by multiple laser beacons producing a constellation of LGSs. A high order wavefront sensor is required for each LGS, and the wavefront information from these sensors is combined to produce a three dimensional description of the atmospheric turbulence over the telescope aperture using tomographic reconstruction techniques. We have concluded that a variable diameter constellation of LGS with one in the center and five equally spaced around a circle provides the optimal sampling of the atmosphere above the telescope with respect to tomography error. The radius of the circle is set at 11" for the narrow field case, and optimized between this radius and 90" depending on the deployment of the IFU heads within a 120" field of regard.

Tilt anisoplanatism is removed using three NGS tip-tilt sensors operating in the near-IR. Three tip-tilt sensors are sufficient for correction of the wavefront error modes associated with tilt anisoplanatism and to reduce the quadratic mode estimation errors in the LGS tomography.

As discussed in §2.2.2.4 the Solar System and Galactic science cases all require single object observations over modest to narrow fields of view, ranging from 2" to 20". This single line of sight could be AO corrected using a single deformable mirror (DM). However, the extragalactic science cases require multi-object, spatially resolved spectroscopic observations; using a number of small (1" x 3") AO corrected fields selected within a larger "field of regard". In addition, based on a combination of limiting magnitude and off axis distance for natural tip-tilt stars, an object selection mechanism is required for these stars, and such a mechanism could operate in a very similar way to the object selection mechanism (OSM) for the multi-object deployable IFU spectrograph. A block diagram of the AO system architecture that we have selected to deliver both high Strehl and access to multiple objects over a wide field is shown in Figure 10.

Starting at the lower left hand side of the figure, an environmental enclosure is provided to house lasers generating a total of ~150 watts in a CW format (or a pulse format with comparable sodium layer return flux). The output from these lasers is transferred (via fibers or a free space beam transfer system) to a multiple beam pattern generator and controller located at the top end of the telescope. The output of this beam pattern generator is projected onto the mesospheric sodium layer by a laser launch telescope located behind the telescope secondary mirror as shown just to the left of center in Figure 10.

Light collected by the Keck telescope is directed to the AO system shown in the lower right in Figure 10. The AO system and instruments are located on one of the telescope's two Nasmyth platforms. The AO system is enclosed in a cooled enclosure (~260 K) to reduce the thermal emissivity of the optical surfaces.

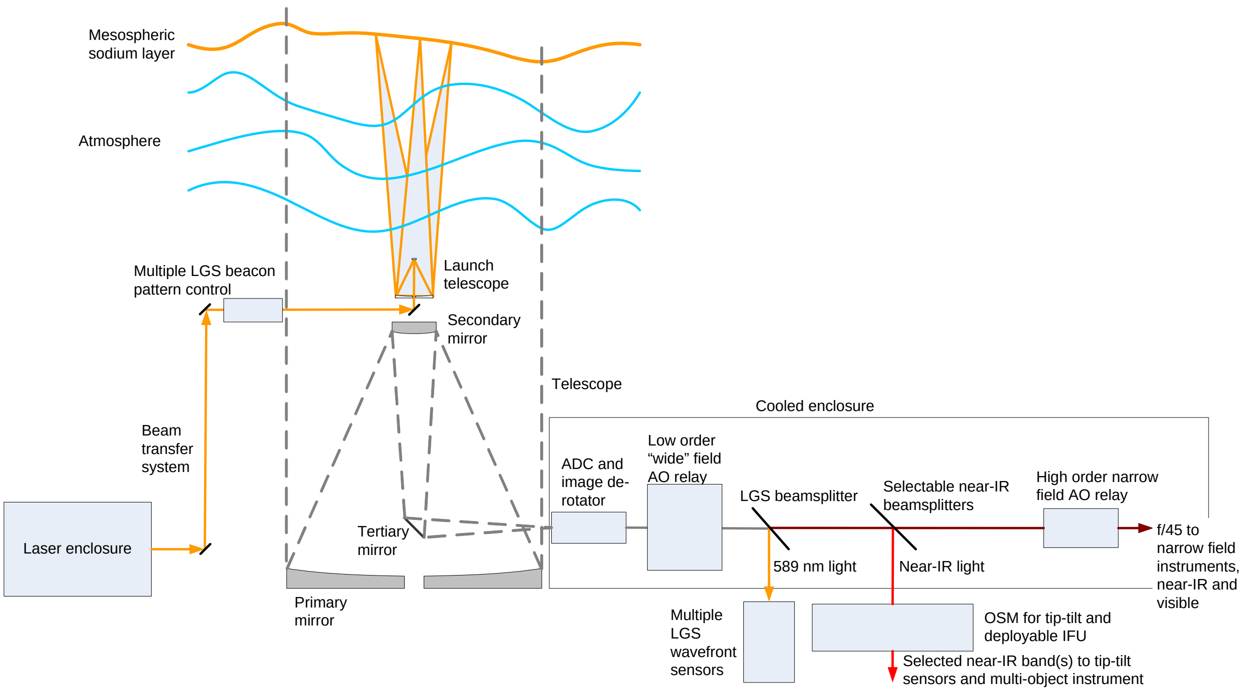


Figure 10: NGAO Block Diagram

Within the cooled enclosure, the light from the telescope passes through an atmospheric dispersion corrector (ADC) and then through a "K-mirror" image de-rotator. A moderate field low order AO relay incorporating a single DM provides partial AO correction to the incoming wavefront. This DM operates in a closed loop in conjunction with the LGS wavefront sensors. At the output of the relay, a dichroic beamsplitter is used to send the 589 nm light from the constellation of LGSs to the LGS wavefront sensors. A second dichroic beamsplitter is used to send near-IR light to the OSM for the tip-tilt stars and the multi-object deployable IFU. Several dichroic beam splitters will be available for selection at this second location to determine which near-IR bands are sent to the OSM and which bands are passed on to the second narrow field AO relay. The second AO relay provides high order correction for the narrow field / single object visible and near-IR instruments.

3.2. Performance Requirements

3.2.1. AO System

The requirements for the AO system are based on the development of a “flow down” from the science requirements to technical requirements. These are documented in detail in a system requirements document. Since we cannot cover all of these requirements in this proposal, we will concentrate on describing the key technical performance and implementation requirements and their flow down from the science requirements.

The science requirements drive a number of key technical requirements including cooling of all optical surfaces to 260 K to reduce the background in the near-IR, a desire to minimize transmission losses, a need to efficiently use the laser light for the multiple LGS, and providing access to the field of view for multiple LGS wavefront sensors, multiple tip-tilt stars, narrow field on-axis science instruments, and a multi-object deployable near-IR IFU.

3.2.1.1. Wavelength Range

The first AO relay in the system must efficiently transmit light over a 0.58 to 2.5 μm wavelength range. This broad range must be efficiently divided between the various sensors (LGS and tip-tilt) and the instruments. The design needs to be optimized to minimize aberrations introduced by transmission through dichroics, and excellent coatings will be required for all surfaces.

Near-IR light will be shared between the tip-tilt sensors and the narrow field instruments. This will require the near-IR beamsplitter for the OSM to be a set of selectable dichroics. This will send some of the near-IR light (for example J and H bands) to the tip-tilt sensors while sending the balance to the narrow field instruments (visible and K band for example).

3.2.1.2. Sensitivity

Observation of faint targets is essential. The point source limiting magnitude estimates given in Table 6 are supported by maximizing the transmission of the telescope and AO system (≥ 60%) and providing high Strehl. Sensitivity is also impacted by instrument characteristics, notably the instrument’s transmission, spatial sampling, detector QE and noise and the instrument’s contribution to the total background. Values given for these parameters are based on experience in the design of current WMKO instruments.

3.2.1.3. Wavefront Error

As discussed in §3.1, the AO system architecture is driven by the required wavefront error to incorporate a number of innovative subsystems that work together to overcome specific effects that limit the quality of the AO correction provided by the system. These include multiple LGS beacons and a corresponding number of LGS wavefront sensors, multiple tip-tilt stars, a tomographic wavefront reconstructor and high order correction.

A minimum of 64 x 64 actuators is required over the telescope pupil to meet the most demanding narrow field residual wavefront error requirement of 140 nm. Such high actuator counts are only practical with MEMS DMs. The multiple LGS require a larger technical field of view than what can practically be accommodated with the very small actuator spacing of MEMS DMs. This would lead to operating the LGS wavefront sensors entirely in open loop, a risky design approach. To address the problem a two DM design is employed, with the first DM with 20 x 20 actuators providing low order correction for the LGS in a closed loop. The second DM is a MEMS DM operated in a feed forward or “go to” control mode. Multiple MEMS DMs are used, one for the narrow field relay, and one for each of the tip-tilt sensors, and for each head of the multi-object deployable near-IR IFU.

A wavefront error budget for NGAO has been developed using Excel spreadsheet tools developed over several years for the engineering evaluation of AO system performance. The primary purpose of the spreadsheet is to compute AO and instrumental wavefront error budgets for different architectures and science cases, along with Strehl ratios computed using the Marechal approximation. The spreadsheet also computes ensquared energy fractions using a core/halo model for the point spread function, and calculates sky coverage estimates for tip-tilt guide stars employed in LGS architectures from common star density models. The spreadsheet has been validated by comparing the spreadsheet predictions to the current performance of the Keck II LGS AO system with good agreement.

Our study of the performance of the selected AO system architecture shows that it is quite flexible, permitting optimization of the residual wavefront error for a wide range of observing conditions. The spreadsheet tool was configured to optimize the H band Strehl ratio, and certain parameters such as LGS constellation radius, high order update rate, and tip-tilt update rate were allowed to vary within appropriate constraints in order to optimize the Strehl ratio. Examples from this study of the wavefront error budget are shown in Table 7. It should be noted that these examples are based on an earlier relay design using a single 64 x 64 actuator DM, a single tip-tilt star and an LGS constellation consisting of just the central LGS and the four equally spaced LGS in a variable radius. No additional LGS were deployed to sharpen the tip-tilt star.

Observation	Int. time	TT reference	LGS diameter, "	TT error, mas	Sky coverage	High order wavefront error, nm	Total wavefront error, nm	Strehl (1.65 μm)
Io	10 s	Science target	N/A	1.7	N/A	96	98	87%
Kuiper Belt	300 s	Field star	41	6.2	10%	150	184	61%
Exo-Jupiter	300 s	Science target	12	3.3	N/A	124	137	76%
Extragalactic	1800 s	Field star	90	18.5	30%	159	329	25%
Galactic Center	30 s	IRS 7	11	2.0	N/A	170	174	64%

Table 7: Wavefront error budget summary

The first column of the table indicates the observing scenario. The second column indicates the integration time assumed for the science exposure. The third column indicates the tip-tilt reference used, and the fourth column gives the diameter of the LGS variable radius constellation. The fifth column indicates the tip-tilt error that results from the assumed angular offset of the tip-tilt star. The sixth column gives the sky coverage fraction over which the tip-tilt error will be less than or equal to the error given in column five. This estimate results from the use of common sky coverage models (Spagna and Bachall-Soneira). The last three columns give the high order wavefront error, the total wavefront error with tip-tilt errors, and the H band Strehl. For the extragalactic case, the figure of merit is ensquared energy rather than residual wavefront error, for the 50 mas spatial sampling of each head of the multi-object deployable IFU the ensquared energy is 37%.

These results show that the variable radius LGS constellation and the performance levels assumed for the tomographic wavefront reconstruction, LGS wavefront sensors and near-IR tip-tilt sensors are capable of providing performance that is generally at the level required by the science cases. As discussed in §2.2.2.3, initial estimates of NGAO system performance based on laser tomography AO resulted in the adoption of three representative values of residual wavefront error for the science case simulations: 140 nm, 170 nm and 200 nm. This has led to further work to develop additional techniques for performance improvement including the additional three freely positionable LGS (see §3.3.5) and the additional tip-tilt sensors.

3.2.1.4. Field of View

The NGAO science cases include a number of narrow field cases for Solar and Galactic science, and moderate to wide field cases for extragalactic multi-object observations. The needs of these cases are met by using the MOAO architecture to provide a moderate (comparatively wide in AO terms) field of view. AO correction for both the moderate and narrow fields is optimized by providing a wider field of regard for the selection of tip-tilt stars and the positioning of LGS beacons. A wider field of regard for the selection of tip-tilt stars also improves sky coverage by increasing the probability of finding stars of adequate brightness.

3.2.1.5. Background

The sensitivity delivered by the NGAO system is significantly affected by the total background seen by the instruments. In the present Keck telescope AO systems background is recognized as a significantly limiting sensitivity, particularly for the K band.

Part of the solution to reducing background is the control of scattered light through careful design and implementation, and the use of hexagonal, rotating cold stops matched to the shape of the telescope pupil in the near-IR instruments. However, thermal emission is a significant factor for near-IR observations, particularly longward of 2 μm. Using data from the current Keck II telescope AO system we have developed a model of the background contributed by sky + telescope + AO system that indicates the AO system optics should be cooled to 260 K.

3.2.1.6. Contrast

Another important area for NGAO science is high contrast observations. The Strehl proposed for NGAO is lower than extreme AO systems such as the Gemini Planet Imager, but at the same time, NGAO will provide higher sensitivity and sky coverage that greatly exceeds that of an NGS-only extreme AO system. While our analysis of the contrast performance needed indicates that a conventional occulting spot coronagraph with an apodized (hexagonal, rotating) Lyot stop will meet the needs of the majority of the NGAO high contrast science cases, we are also investigating the use of more advanced techniques such as non-redundant aperture masking.

The level of contrast achieved with NGAO will also depend on the control of systematic errors such as non-static, non-common path aberrations, servo lag error and various sources of speckle. Speckle suppression techniques including spatially resolved spectroscopy will be available for NGAO observations.

3.2.1.7. Photometric Accuracy

Requirements for photometric measurements in the NGAO science cases range from 0.05 to 0.1 magnitudes in relative photometry, and ≤ 0.05 magnitudes for absolute photometry. The fundamental condition for high photometric accuracy is stability of the PSF. Because of the high Strehl delivered by the NGAO system, a more stable PSF is expected. Many of the science cases that require the highest photometric accuracy are observing a science target of sufficient brightness ($H < 16$) to permit use of the science target as an on-axis tip-tilt reference, further improving Strehl performance.

Analysis of NGAO photometric accuracy requirements also leads to a number of other technical requirements related to the PSF. These include obtaining precise knowledge of the AO system PSF through provisions for PSF calibration and monitoring. NGAO may need to provide a PSF monitoring imager deployable over the AO system technical field of view to allow simultaneous PSF imaging during observations. Recent work at Palomar (Britton 2006) has shown that real time turbulence monitoring giving C_n^2 data during the observation is also useful in improving the results of PSF post processing. This post processing will also be supported by facility PSF deconvolution software.

3.2.1.8. Astrometric Precision

Astrometry is important for a number of the Galactic and Solar System science cases. The most demanding requirements are for observations of the Galactic Center where precision of 100 μas is required. The current Keck II LGS AO system with the NIRC2 instrument is able to achieve best-case precision of 250 μas. The high Strehl of the NGAO system (~3 times that of the current LGS AO system under similar conditions) will make a significant contribution to the accuracy of astrometric measurements by reducing source confusion. In addition, studies of the astrometric precision of the current Keck II LGS AO system indicate that geometric distortion, differential tilt anisoplanatism between the science target and off axis tip-tilt stars (increasing with increasing distance between the two), and differential atmospheric refraction all contribute to the error in astrometric measurements.

The same features provided to monitor the PSF and monitor atmospheric turbulence for photometric accuracy would contribute to NGAO astrometric precision. Geometric distortion in the AO system and instruments will be minimized during design and facilities will be incorporated for mapping residual distortion during commissioning. Improved mechanical stability is also a fundamental part of the design of the NGAO system and instruments.

The NGAO system will incorporate an ADC to reduce the effects of atmospheric refraction, and differential tilt anisoplanatism will be reduced by the use of multiple, optimally located tip-tilt stars. Alignment tools for these multiple tip-tilt stars will minimize plate scale changes due to the AO correction.

3.2.1.9. Sky Coverage

The sky coverage fractions required by the extragalactic and Galactic science cases requires optimizing the offset and brightness of the tip-tilt stars. This is accomplished by increasing the faint magnitude limit for tip-tilt stars through the use of tip-tilt sensors operating at near-IR wavelengths combined with MOAO correction using deployable LGS beacons specifically for tip-tilt reference sharpening, and by providing a 180" field of view for tip-tilt star selection.

3.2.2. Technical Requirements Summary

A summary of the NGAO technical requirements may be found in Table 13 in the appendix.

3.2.3. Instrumentation

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 multi-object deployable near-IR IFU spectrograph that is of necessity a more complex instrument.

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 NGAO development timeframe. 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 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 other considerations we have identified the instrument priorities shown in Table 8.

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		

Table 8: NGAO instrument priorities

The near-IR imager will be the first-light commissioning instrument for NGAO. The multi-object deployable near-IR IFU is a high priority instrument, but because of its complexity, it will also have the longest development timeline and it is important that its development be started as soon as possible. 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.

Initial requirements for the imagers are summarized in Table 9.

Instrument	**Wavelength coverage** (μm)	**Field of view**	**Sampling**
Visible Imager	0.7 to 1.0	20" x 20"	Nyquist (6 mas)
Near-IR Imager	1.0 to 2.45	20" x 20"	Nyquist (10 mas)

Table 9: NGAO imager requirements

The initial requirements for the multi-object deployable near-IR IFU are as follows:

- Wavelength coverage: 1.0 to 2.45 μm
- Multiplex: minimum of 6 deployable IFU heads
- Spatial sampling per IFU head: 60 x 20 samples minimum
- Sampling scale: 50 mas
- Spectral resolution: R ~4,000
- Spectral sampling: ~2,000 pixels/spectra

The initial 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, 50, 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

With the exception of the field of view, OSIRIS meets many of the requirements for this instrument.

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

- Wavelength coverage: 0.7 to 1.00 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: 50, 35, 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

3.3. AO System Description

3.3.1. Optical Design

The optical configuration for the AO portion of the NGAO system is shown in Figure 11. We refer to this design as the "cascaded relay" because it uses two AO relays in series. The partially corrected wavefront provided by the first low order AO relay improves the performance of the LGS wavefront sensors and the near-IR tip-tilt sensors. This relay also provides the low order correction for the MOAO mode used in the multi-object deployable IFU. After consideration of both MCAO and MOAO architectures for the wide field requirement NGAO has adopted the MOAO architecture. In this design, each head of the multi-object deployable IFU will use a 32 x 32 MEMS DM operating in open loop to provide high order AO correction. A MEMS DM will also be incorporated in each of the tip-tilt sensors in order to improve the sensitivity and accuracy of these sensors.

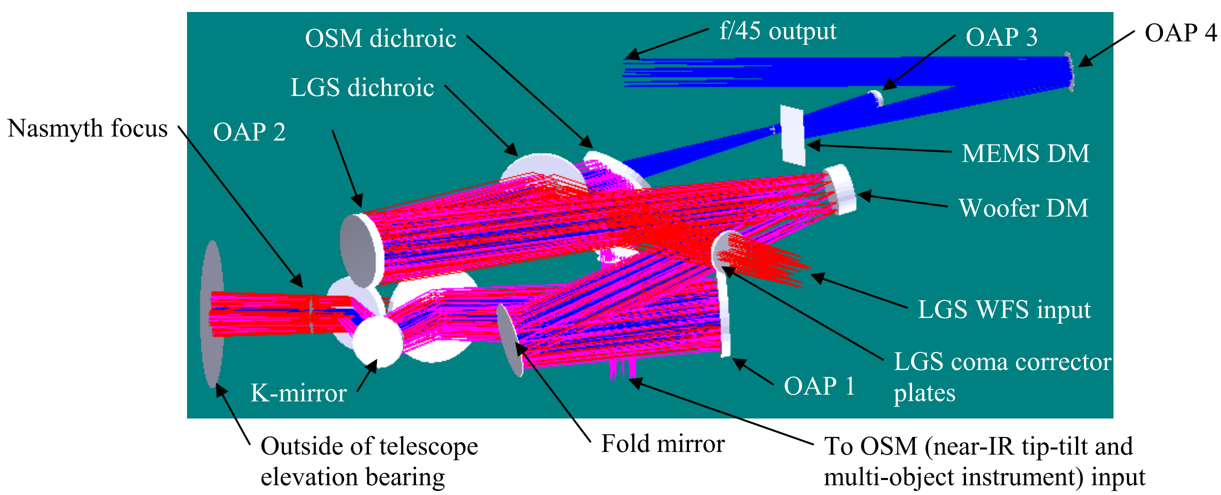


Figure 11: AO system optical configuration

The Keck telescope f/15 Nasmyth focal plane is located ~270 mm past the telescope's elevation bearing. The AO system optics are enclosed in a cooled enclosure, and a window (not shown) is provided to isolate the enclosure from the dome environment. The light then passes through an atmospheric dispersion corrector (also not shown), a "K-mirror" image de-rotator and then into the first AO relay. This is a one to one relay composed of off-axis parabola (OAP) 1, a fold mirror, the first DM with 20 x 20 actuators, and a second OAP.

From the second OAP the light (now at f/15 again) travels to the first dichroic beam splitter located at a 45º angle of incidence. 589 nm light is reflected by this dichroic to the LGS wavefront sensors while the remaining light travels on to the second dichroic beam splitter. This dichroic is also located at a 45º angle of incidence but rotated 90º to fold the beam down to the OSM for the tip-tilt sensors and the multi-object deployable IFU. A benefit of this arrangement is that the astigmatism introduced into the transmitted beam path by the two dichroics is cancelled.

The first DM is conjugated to the telescope's pupil. Between the two OAPs the collimated beam is ~100 mm diameter, resulting in a 5 mm actuator spacing for the first DM. The fold mirror is located conjugate to ~10 km altitude providing a location where a second DM could be retrofitted to implement a MCAO mode. This first AO relay provides a 120" science field and a 180" technical field to the OSM. The fold mirror and the first DM form a periscope that changes the beam height to allow a second layer in the opto-mechanical packaging of the system.

The second dichroic beam splitter will be realized as a set of selectable beam splitters in order to share the near-IR wavelengths between the tip-tilt sensors and the narrow field instruments. A second corrector plate is included in the beam path to the OSM to correct the astigmatism in this path introduced by transmission through the first dichroic.

The light that passes through the second dichroic continues on to a second AO relay. OAP3 collimates the f/15 beam to 25.6 mm diameter resulting in a 0.4 mm actuator spacing for the second DM. This is a MEMS DM with 64 x 64 actuators. OAP4 forms a one to three relay with OAP3 resulting in an f/45 output beam for the narrow field instruments.

The optical path to the LGS wavefront sensors results in a tilted image plane where the tilt changes as a function of zenith angle, requiring that each LGS wavefront sensor be independently focused. For the LGS images, the first AO relay is also not operating at the designed conjugates, resulting in aberrations that look like astigmatism but are field position dependent. These aberrations are cancelled by a pair of spherical aberration plates that are translated laterally with respect to each other as a function of zenith angle. This correction results in very small residual LGS image aberrations (~ 30 mas) that are largely independent of zenith angle. An OSM is also required for the LGS wavefront sensors covering a 202" technical field of view.

This configuration will be more compact than the current AO systems on the Keck telescopes. The pupil size is ~30% smaller, and results in a correspondingly smaller area occupied by the complete optical path (~50% less than each of the current systems). None of the instruments is required to rotate, and the location options and configurations for the instruments, including the multi-object deployable near-IR IFU, do not have particularly tight constraints.

3.3.2. LGS Beacon Projection System

The LGS beacon projection system consists of a beam pattern generation and pointing system and a launch telescope. The launch telescope will incorporate a tip-tilt mirror for correction of the laser uplink tip-tilt and the beam pattern generator may incorporate a beam splitting arrangement so that fewer laser beams will need to be transferred to the top end of the telescope. The beam pattern generator will provide one fixed on axis LGS beacon, a variable diameter pattern of five LGS beacons positioned by linearly translated fold mirrors, and three additional freely positionable LGS beacons using tip-tilt mirrors for beam pointing.

3.3.3. LGS Wavefront Sensors

The LGS wavefront sensor detectors are Shack-Hartmann (SH) designs with 64 x 64 subapertures. For the LGS wavefront sensor detectors we anticipate using a very low noise CCD based on the CCID-56b/d, developed for AO wavefront sensing through a project funded by the Adaptive Optics Development Program (AODP), to minimize the laser power required in each beacon in order to achieve the required SNR.

3.3.4. Tip-tilt Sensors

The three tip-tilt sensors operate at near-IR wavelengths to improve the availability of suitable stars of sufficient brightness. Optimal performance is obtained using J and H band light, but a selectable beam splitting dichroic will allow sending one or more near-IR bands in combination to the tip-tilt sensors with the remainder of the near-IR and the visible light to 0.7 μm passing to the narrow field instruments. At least one sensor will be of at least order 2 x 2 to provide sensing of focus and astigmatism. Each tip-tilt star will be AO corrected using a MEMS DM with a LGS beacon positioned near each tip-tilt star to maximize this correction.

3.3.5. Object Selection Mechanisms

NGAO has two object selection mechanisms, one for the LGS and one for the tip-tilt stars and target selection for the multi-object deployable IFU. A cartoon of the NGAO focal plane for these two modes is shown in Figure 12.

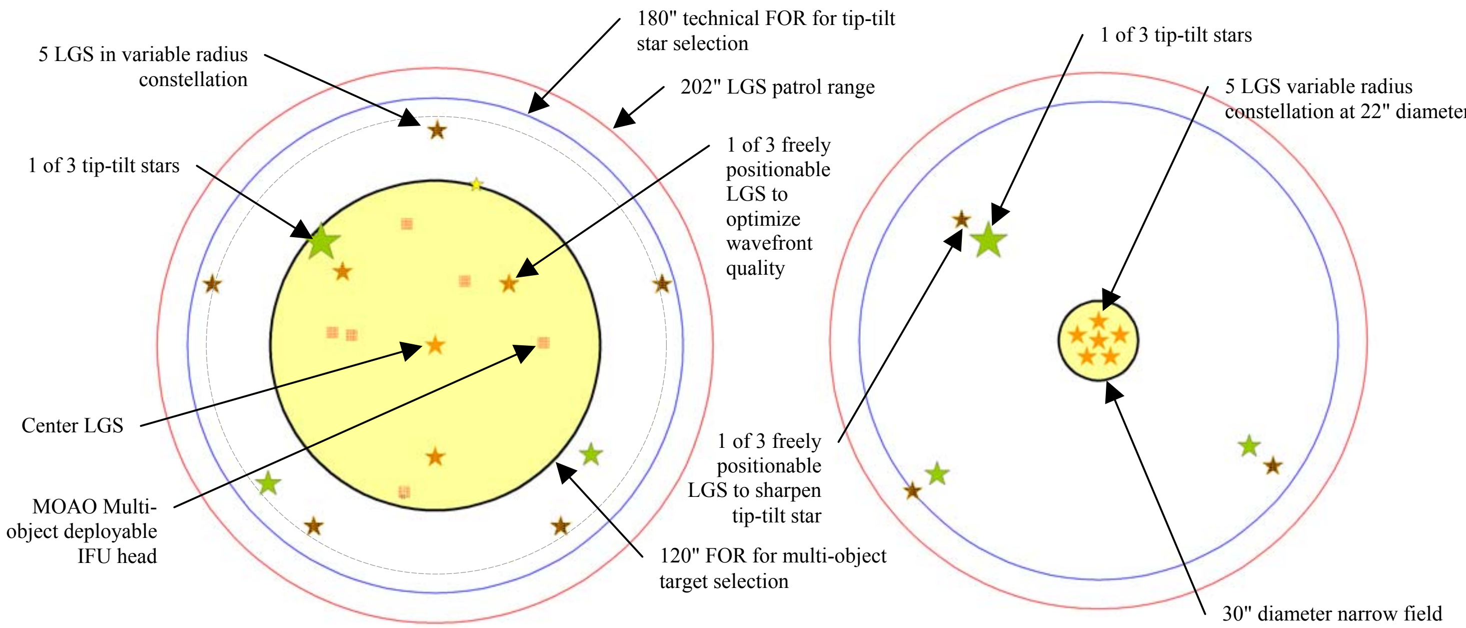


Figure 12: NGAO focal plane

The wide field mode for multi-object observations is shown on the left and the narrow field mode for single object observations is shown on the right. Each mode uses a total of 9 LGS beacons.

In wide field mode the NGAO focal plane consists of a 120" diameter field of regard (FOR) for the selection of targets for the multi-object deployable IFU. This is surrounded by a 180" technical FOR used for selection of tip-tilt stars, and a slightly larger 202" field for LGS acquisition. In wide field mode the variable radius constellation of 5 LGS is deployed to a diameter selected to optimize the wavefront error across the 120" science FOR. A sixth LGS is located in the center of the FOR. Three freely positionable LGS are deployed in the FOR to optimize image quality, with respect to either the multi-object field of views or the tip-tilt stars.

In narrow field mode the NGAO science field is 30" in diameter. The variable radius constellation of 5 LGS is reduced to 22" diameter and the three freely positionable LGS are used to sharpen the selected tip-tilt stars.

3.4. Mechanical Design

The opto-mechanical configuration of the NGAO system on a Keck telescope right Nasmyth platform is shown in Figure 13. For reference the floor of the existing Keck II AO enclosure is indicated by the surface with the red outline. The AO system optical components will be further enclosed to allow cooling to 260 K, the exact configuration of this enclosure is to be determined.

Starting just above the center of the figure on the left side the 9 LGS wavefront sensor units are shown. Each wavefront sensor is mounted on an independently controlled focus stage. LGS field selection is performed by the OSM located just to the right of the LGS wavefront sensor assembly. At the center of the figure the two AO relays are shown mounted on the opto-mechanical unit (OMU) bench. The K-mirror and OAP 1are mounted below this bench, and the beam then passes up to the first and second AO relays mounted above the bench.

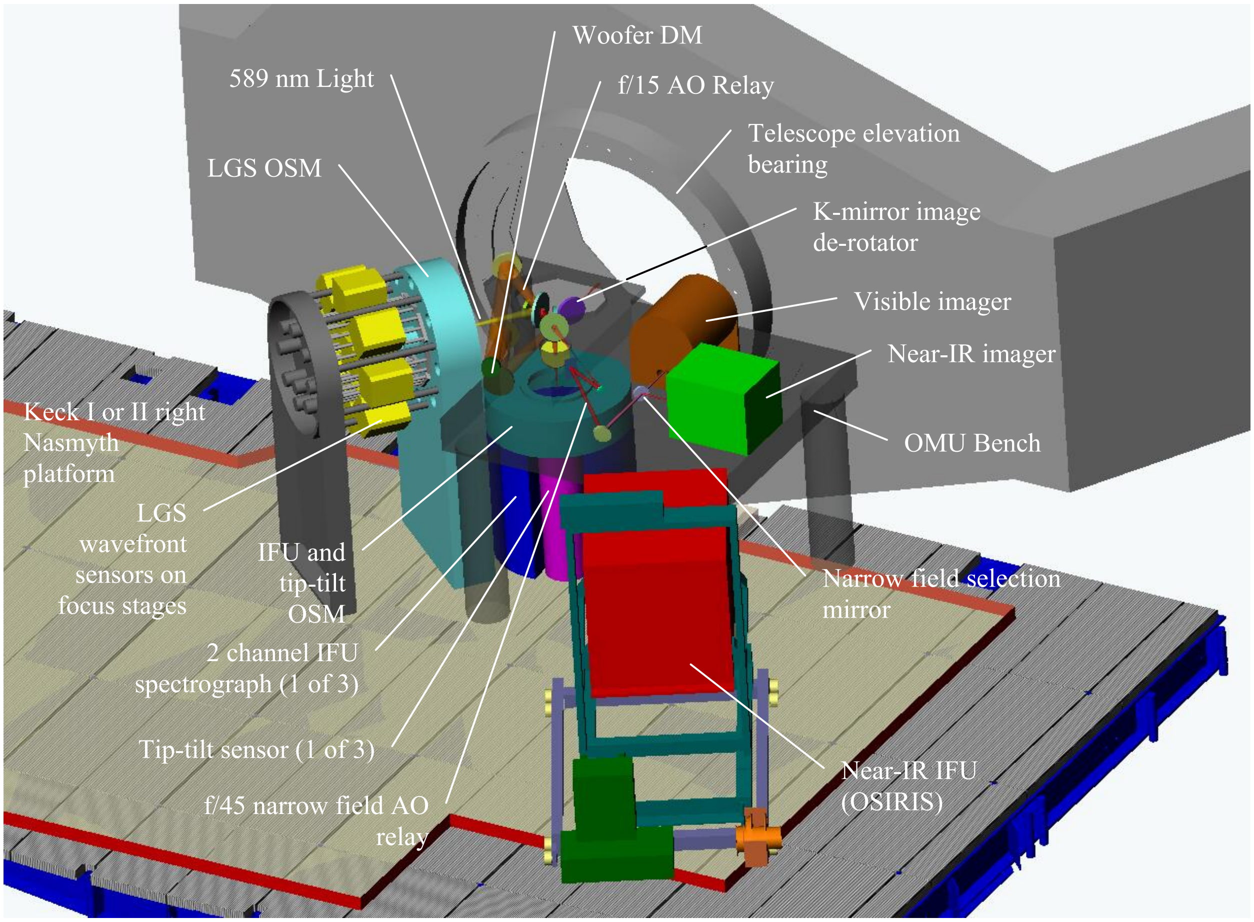


Figure 13: NGAO opto-mechanical configuration

The OSM for the multi-object deployable IFU spectrograph is located beneath the bench and feeds the 3 tip-tilt sensors and the IFU. The IFU spectrographs are contained in three identical cryostats, each providing two IFU spectrographs. The tip-tilt sensors are also enclosed in cryostats.

Just to the right of center, above the OMU bench the f/45 narrow field relay output is directed to a selection mirror used to switch the beam between the single object near-IR IFU and the near-IR imager. The mirror is translated out of the beam for the visible imager. The two imagers are mounted on the OMU bench. The near-IR IFU is mounted on a separate service cart, in this illustration the OSIRIS instrument is shown for the near-IR IFU.

3.5. Electronics and Software

Electronics and software subsystems are associated with each of the major components of the NGAO system. A block diagram of the NGAO electronics/software subsystems and related external subsystems is shown Figure 14.

Communications between the various subsystems are represented by four control and data paths shown in the figure. The real time data flow (magenta) between the wavefront sensors and the DMs is isolated from other communications flow to provide maximum performance. The "AO Configuration and Status" control path (light blue) is used by the AO sequencer to orchestrate the operation of the AO system. The sequencer establishes configurations for each observation and provides status and control for the non-real time subsystems to the AO host computer via the "Supervisory Control and User Interface" (green). This interface also provides the AO host computer with control and status for the various supervisory controls. The AO sequencer coordinates AO operations with the external subsystems, the instrumentation, telescope drive and control and the primary mirror control system via the "Auxiliary Configuration, Offloading and Status" interface (purple). This includes tip-tilt offloading to the telescope secondary and control of telescope tracking during an observation.

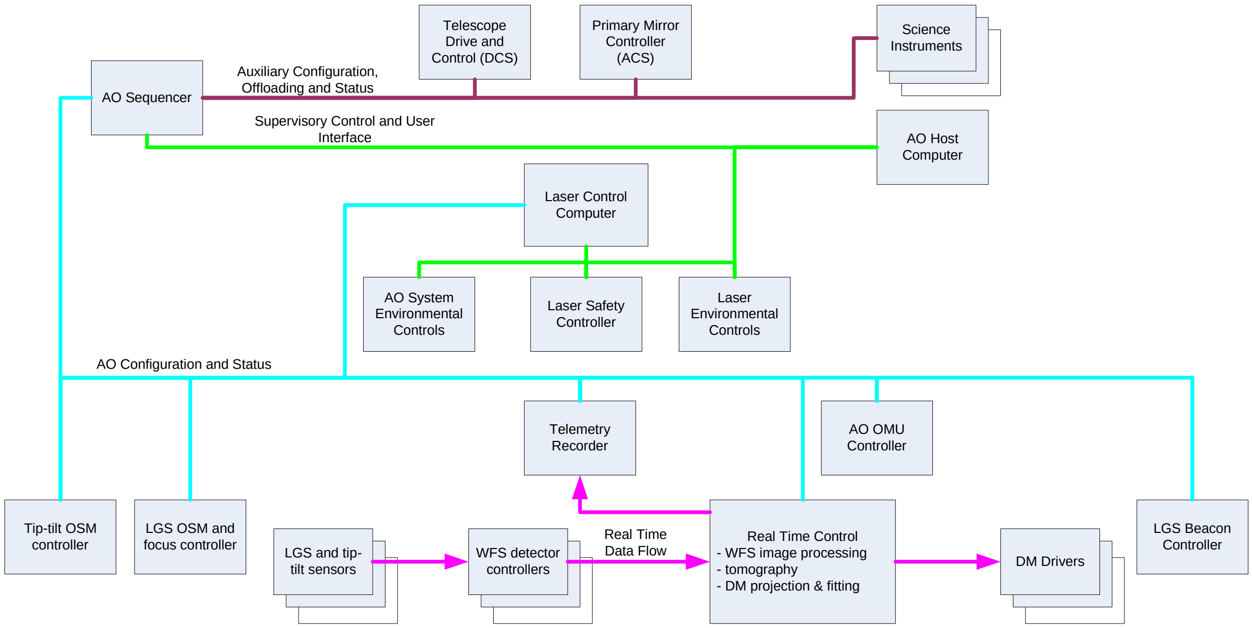


Figure 14: NGAO electronics and software subsystems

The majority of the AO electronics subsystems will be straightforward designs based on heritage systems, particularly for supervisory controls such as AO enclosure environmental and laser safety. Similarly, instrument electronics will be based on the most current heritage designs from the OSIRIS and MOSFIRE instruments at WMKO. The sensors for the tip-tilt stars will also be based on existing detector technology and readout systems. LGS wavefront sensing electronics will be based on the AO wavefront sensing systems being developed for the TMT through the AODP.

The main challenges in the design of the NGAO electronics and software are the demanding real time control requirements for AO in a multi-guidestar system employing tomographic wavefront reconstruction techniques and multiple DMs. Our investigation of the algorithms and data flow needed for AO real time processing and control has suggested that a massively parallel architecture using current state-of-the-art field-programmable gate arrays (FPGAs) can readily accomplish this task.

3.5.1. Real-time Control Requirements

The real-time control requirements for NGAO are summarized in Table 10.

3.5.1.1. Massively Parallel Processing

The proposed massively parallel processing (MPP) system pipeline architecture depicted in Figure 15 implements a three step process: wavefront measurement, tomography, DM fitting. Multiple wavefront sensors, corresponding one to each LGS and tip-tilt star, feed data to a centralized tomography unit. These are inherently parallel operations. Calculation is further parallelized across the spatial dimensions (two dimensions x and y for wavefront sensor and deformable mirrors, and three dimensions x, y, and z for tomography, where z is the vertical direction). For algorithmic reasons, data in x, y planes parallel to the aperture are represented by their Fourier coefficients. Calculations are spread out among processors dedicated to pieces of the x-y Fourier space, slices in the z vertical space, individual wavefront sensors, and individual DMs.

The tomography unit determines an estimate of the differential optical path differences within volume elements of a model atmosphere. This information is then used in a process of determining the desired phase correction at each DM, given a tomographically determined estimate of differential phase aberrations over the atmospheric volume. For MOAO this is the line integral of the turbulence estimate through the volume in the direction of interest. Since the DMs commonly have inter-actuator influence functions, a deconvolution and/or lookup table access must be done for the actuator commands so that the resulting DM shape best fits the new wavefront estimate. Fitting involves deconvolving the DM's unit response function so that a voltage command can be determined given the desired surface shape. In the case of MEMS in open loop operation, it is necessary to use an additional cascade of two non-linear lookup tables.

The MPP architecture described above has a distinct advantage over a traditional single CPU implementation in that it can scale with the number of guide stars, number of DMs, and number of subapertures by simply adding processor cards without affecting the data throughput rate or the software program significantly.

Control bandwidth	>90 Hz
Wavefront sensor frame rate	1.5 to 2 kHz
Number of LGS wavefront sensors	9
Number of tip-tilt sensors	3
Number of deformable mirrors	**Narrow field mode**: 1 20 x 20 “woofer” DM, 1 64 x 64 “tweeter DM”, 3 32 x 32 DMs for MOAO correction of the tip-tilt stars. **Wide field mode**: 1 20 x 20 “woofer” DM, 3 32 x 32 DMs for MOAO correction of the tip-tilt stars, 6 32 x 32 DMs for MOAO correction in the multi-object deployable IFU.
Reconfigurable for number of guide stars and DMs. Allows differing asynchronous data rates from various wavefront and tip-tilt sensors	
Adapts and optimizes for changing seeing and signal-to-noise conditions and incorporates information from external measurements of the C_n^2 profile	
Full telemetry and diagnostics streams	

Table 10: NGAO real time control requirements

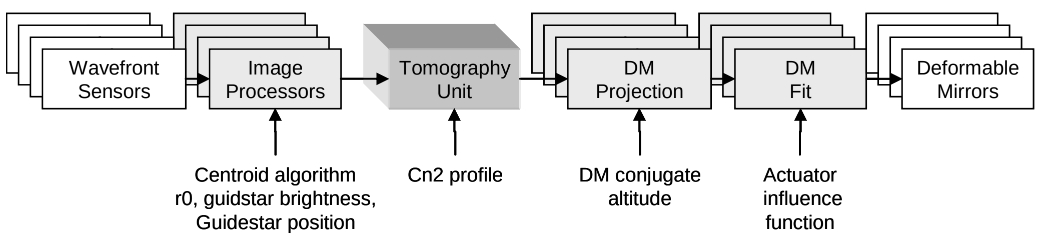


Figure 15: Multi-guidestar AO processing architecture

3.5.1.2. Tomography

Tomography is accomplished with an iterative back-propagation algorithm depicted in Figure 16 (Gavel 2004, Gavel et al. 2005). The method is analogous to the filtered-back-projection techniques used in modern medical tomography 3-d data analysis. These calculations can be mapped to the massively parallel computer architectures described earlier. During processing, each iterative correction is along a conjugate-gradient direction, resulting in convergence in only a few iterations. Overall, the MPP implementation combined with the fast converging algorithm enable the process to be repeated at the very demanding frame rates of real-time adaptive optics, about once per millisecond .

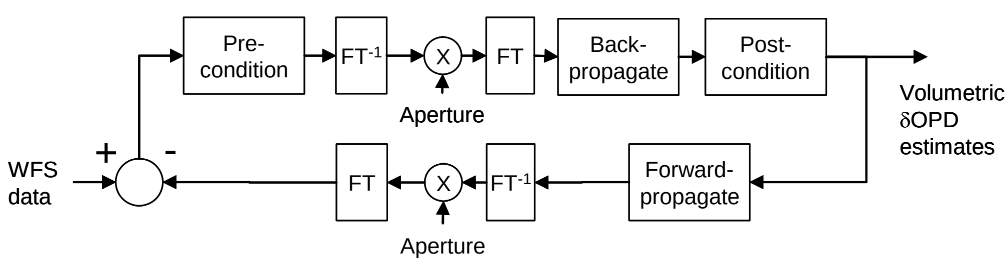


Figure 16: Tomography algorithm

3.6. Preliminary Design Plans

In the Observatory's development program, the preliminary design phase has two primary objectives. The first objective is to deliver documented designs for each system, sub-system and component, hardware or software, of sufficient detail to establish through inspection and analysis the feasibility of the proposed design, and the likelihood that the design will meet the requirements. The second objective is to present the project plan to completion, including a detailed schedule and budget.

The principal activities of the preliminary design phase are design, prototyping, simulation and analysis. The key deliverables are preliminary technical specifications, requirements for subsystems, a preliminary Operations Concept Document, Interface Design document(s), and a Preliminary Design report.

The WBS for the NGAO project, with an emphasis on the preliminary design phase is shown in Figure 18. The principle work activities in the phase are associated with the preliminary design of the AO facility and laser facility and the development of preliminary interface control documents (ICDs) for the interfaces between the AO system and the Observatory and with the instrumentation.

Specific prototyping activities identified for the preliminary design phase are the development of a prototype near-IR tip-tilt sensor. This sensor will incorporate a MEMS DM for wavefront correction and will be tested with an actual AO system. Prototype work will also be performed on tomographic wavefront reconstruction in collaboration with the Laboratory for Adaptive Optics (LAO) at UCO/Lick Observatory.

4. MANAGEMENT

4.1. Project Structure and Organization

The development of NGAO is a collaboration between WMKO and the Observatory's primary partners and founders, the University of California and the California Institute of Technology (CIT). For the development of the AO system, the Principal Investigator is Peter Wizinowich, Manager of Adaptive Optics and Interferometry at WMKO and a recognized leader in the development of astronomical adaptive optics. Claire Max, Professor of Astronomy and Astrophysics at the University of California, Santa Cruz (UCSC) is the Project Scientist. She is an active astronomer and one the pioneers in the development of laser guide star adaptive optics. She is also the Director of the NSF Center for Adaptive Optics (CfAO) at UCSC.

The technical development of NGAO is led by Peter Wizinowich and co-investigators Donald Gavel (UCSC) and Richard Dekany (CIT). Don is the Director of the Laboratory for Adaptive Optics (LAO) at the UCO/Lick Observatory. The LAO is currently developing the high contrast AO system for the Gemini Planet Imager and is working on the development of MCAO, tomographic wavefront reconstruction and MEMS DM devices. Richard Dekany is the Associate Director for Development at the Caltech Optical Observatories. He is the Principal Investigator for the PALM 3000 visible light LGS AO system being developed for the Palomar Observatory as an upgrade to the existing Palomar AO system.

The organization chart for the development of the NGAO AO system is shown in Figure 17. A project manager, appointed from the WMKO staff, will work with team leads for each of the major disciplines to coordinate day to day activities in the project. Discipline leads for the preliminary design phase will be determined in early 2008, prior to the system design review for the AO system. Project staff will be provided by all three partners, and administrative support for the project will be provided at all three institutions.

Overall program management resides with the WMKO Instrument Program Manager Sean Adkins and the WMKO process for new instrument development will be followed.

4.2. Project Management

The organization and management of the project is documented in a Systems Engineering Management Plan (SEMP) that describes the project objectives, major milestones, project organization and project management process. The SEMP is updated as required as part of the review documentation for each design phase. The SEMP also defines the project decision process and major decision points, the risk assessment and risk management process, and configuration management plans for hardware, software and documentation.

During the system design phase, the project management responsibility is shared by the PI, project scientist and co-Investigators. Starting with the preliminary design phase the project will have a full time project manager, appointed from the WMKO staff. The co-investigators at UCSC and CIT will work with the project manager and the various discipline leads from their respective organizations to manage activities at each institution. Progress with respect to the project task plan and schedule will be reviewed monthly, as will actual and projected expenditures with respect to the project budget. As part of the system design review documentation, the SEMP will be updated and revised to reflect the management process for the remaining phases of the project.

4.3. Risk Assessment and Management

An initial assessment of major risk areas and possible mitigation strategies for the NGAO project was developed as part of our June 2006 proposal to the WMKO SSC. The results of that risk assessment have been a major driver for the trade studies conducted during the current phase of the project.

At present, the risks that are the most significant issues for NGAO are the following:

1. Achieving the astrometric precision requirements – the project is working closely with the UCLA Galactic Center team and researchers at CIT studying proper motions to understand the limitations imposed by the current Keck II LGS AO system and instrumentation. Effort on understanding this error budget will continue during the preliminary design phase.
2. Achieving the photometric accuracy requirements – the performance of the NGAO system in this area is closely tied to other key issues in the project, particularly wavefront error and PSF stability. Several areas of investigation are underway to establish plans for the calibration and monitoring of the PSF. Further effort in this area will be one of the major activities in the preliminary design phase.
3. Adequate PSF calibration – a key element in the technical approach to meeting the astrometric precision and photometric accuracy requirements for NGAO is the calibration of the PSF. This is also important for maximizing the performance of the high contrast capability of NGAO. As a result of trade studies to understand PSF performance and calibration issues, members of the NGAO team submitted a two year proposal for the development of PSF reconstruction techniques to the CfAO. This proposal has been funded and work will begin in November 2007.
4. Tomographic wavefront reconstruction – although experimental demonstrations of tomography have taken place, for example the MAD experiments at the VLT, and the science debut of LGS AO tomography is approaching at Gemini South, to date no science observations have been performed using tomographic wavefront reconstruction. Preliminary on-sky experiments were performed at Palomar that provide an upper limit on the tomographic errors and NGAO trade studies have compared multiple tomography codes and used simulations based on these codes to predict the performance of tomographic wavefront reconstruction. During the preliminary design phase we will continue to perform laboratory experiments in support of NGAO's tomography implementation at the LAO.
5. Sky coverage – meeting the 30% sky coverage requirement for NGAO relies on the use of high performance near-IR tip-tilt sensors. Our performance analysis suggests that an MOAO corrected low order wavefront sensor using low noise detectors can meet the NGAO requirements. Prototyping this sensor and testing its performance is part of the preliminary design phase.
6. Multiple LGS projection and wavefront sensing – the NGAO LGS projection system will incorporate opto-mechanical hardware to position 9 laser guidestars in the NGAO technical field of view, and opto-mechanical hardware to acquire the LGS images on 9 corresponding LGS wavefront sensors. Design and implementation of these two subsystems will be challenging due to constraints on packaging. The design of these two subsystems will be a priority during the preliminary design phase in order to reduce the key implementation risks in this area.
7. OSM for the near-IR tip-tilt stars and multi-object deployable IFU – the current NGAO optical design indicates that combining the OSM for the tip-tilt stars and the multi-object deployable IFU is not only beneficial from a cost and complexity standpoint, it may also be essential to permit packaging this key

subsystem within the performance and physical constraints imposed by NGAO and the existing WMKO facilities. A trade study is currently underway on the arrangement and control of the OSM. During the preliminary design phase the OSM design will be detailed in order to reduce the key implementation risks for this subsystem.

As part of the System Design Manual, one of the deliverables from the system design phase, a revised risk assessment and mitigation plan will be prepared covering requirements risks, technology risks and risks related to schedule and budget. A detailed process for risk assessment and mitigation will also be included in the SEMP when it is revised for the preliminary design phase.

4.4. Work Breakdown Structure

A work breakdown structure (WBS) diagram for the NGAO project is shown in Figure 18. This diagram emphasizes the preliminary design phase WBS elements for the AO design. There are four major WBS elements in the preliminary design phase: Systems Engineering, AO Facility, Laser Facility and External Interfaces. The Systems Engineering WBS includes the refinement and updating of the AO facility architecture and requirements, and the maintenance and updating of the AO performance budgets, technical risk assessment and mitigation plan, and the System Design Manual.

Subject to available funding, the system design phase of the key NGAO instruments, the multi-object deployable IFU and the two imagers, will begin at the start of the NGAO preliminary design phase.

4.5. Schedule

The schedule for the NGAO preliminary design phase for the AO design is shown in Figure 19. A larger 11 x 17 version of this figure and an overview of the entire project schedule to completion are included with this proposal. The duration of the preliminary design phase is currently estimated at 21 months, beginning in April 2008 and ending in December 2009. This will be followed by a detailed design phase of approximately 12 months, a full scale development phase lasting approximately 23 months, and an installation phase lasting approximately 5 months followed by first light in April 2013. Shared risk observing begins 6 months later in September 2013. Key milestones for the project are shown in Table 11.

4.6. Deliverables

The deliverables for the AO portion of the NGAO project consist of documentation and the actual AO Facility, Laser Facility and related interfaces. Major documentation items include:

System Design:
- Science Case Requirements Document
- System Requirements Document
- System Design Manual
- Systems Engineering Management Plan
- System Design Report

Preliminary Design:
- Requirements Documents for Key Subsystems
- Operations Concept Document
- Preliminary Technical Specifications
- Interface Control Documents
- Preliminary Design Report

Detailed Design:
- Detailed Design Drawings and Bills of Material
- Final Technical Specifications
- Acceptance Test Plans

Detailed Design Report

Full Scale Development:
- Hardware and Software Manuals and Maintenance Documentation
- Pre-ship Review Reports

Installation/Commissioning:
- Acceptance, Operational Readiness and Science Verification Review Reports

A list of specific deliverables for the AO hardware and software will be developed during the preliminary design phase.

4.7. Milestones and Reviews

WMKO's instrument program provides for specific reviews involving the participation of independent external reviewers. Reviews are organized and conducted by the WMKO instrument program manager and the report of the review panel is formally made to the WMKO director. The review reports are also sent to the SSC, the instrument program manager and the NGAO project team. We have identified 9 reviews that will be conducted for the work in this project. The major milestones and reviews for this project are shown in Table 11.

Year	Month	Milestone
2008	April	System Design Review
2009	December	Preliminary Design Review
2010	December	Detailed Design Review
2011	July	Full Scale Development Intermediate Review 1
2012	March	Full Scale Development Intermediate Review 2
2012	December	Pre-ship Review
2013	April	First Light
2013	September	Acceptance Review, shared risk observing begins
2013	November	Science Verification Review
2013	November	Operational Readiness Review

Table 11: Milestones and Reviews

4.8. Reporting

This project will use the system of project monitoring and reporting currently in place at WMKO for the development of new instruments. Each month a project meeting will be held and attended by all of the project participants. Video conferencing and teleconferencing facilities are available to all participants and will be used to hold the monthly project meetings as well as special purpose meetings as required. The project team will prepare monthly reports for the WMKO instrument program manager in accord with WMKO's standard development project reporting format. The WMKO SSC receives regular reports on the progress of NGAO at the meetings of the SSC.

4.9. TSIP Program Oversight

Monthly project reports prepared by WMKO will be sent to TSIP, and TSIP program management representatives will be invited to participate in monthly teleconferences to review the monthly report. TSIP representatives will also be invited to each of the review meetings, and TSIP will be invited to appoint two reviewers to each external review panel (System Design Review, Preliminary Design Review, Detailed Design Review, Pre-ship Review and Science Verification Review).

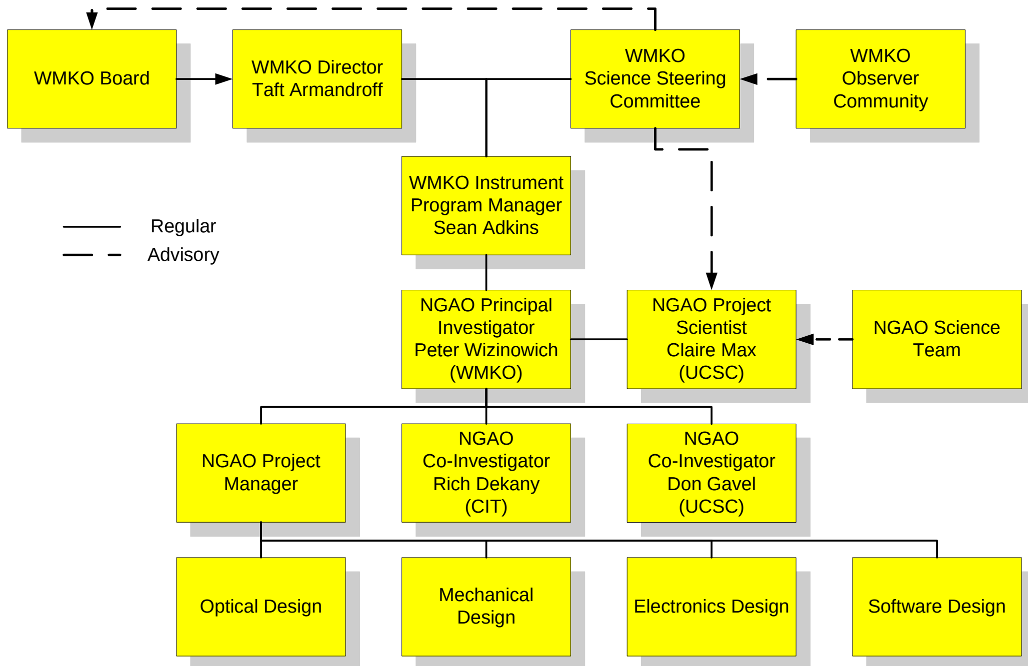


Figure 17: Organization chart

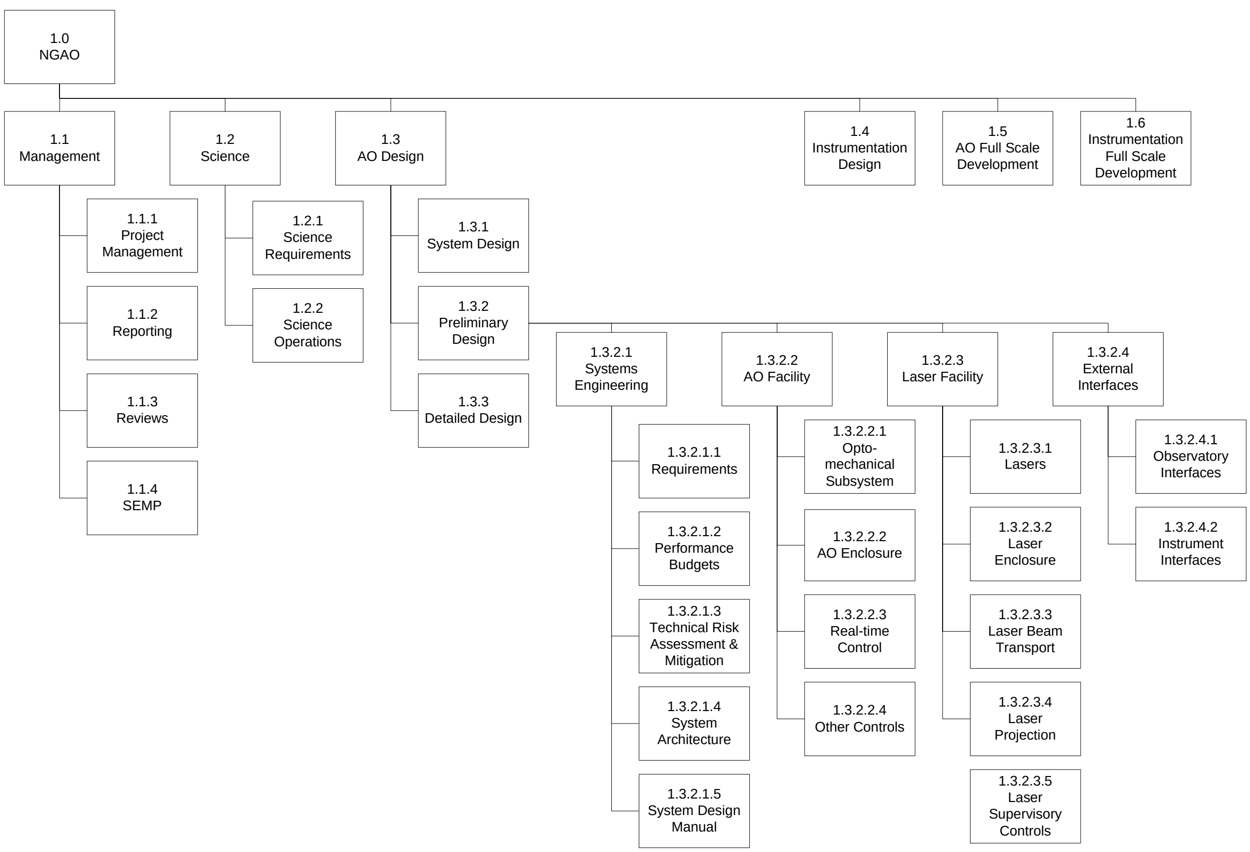
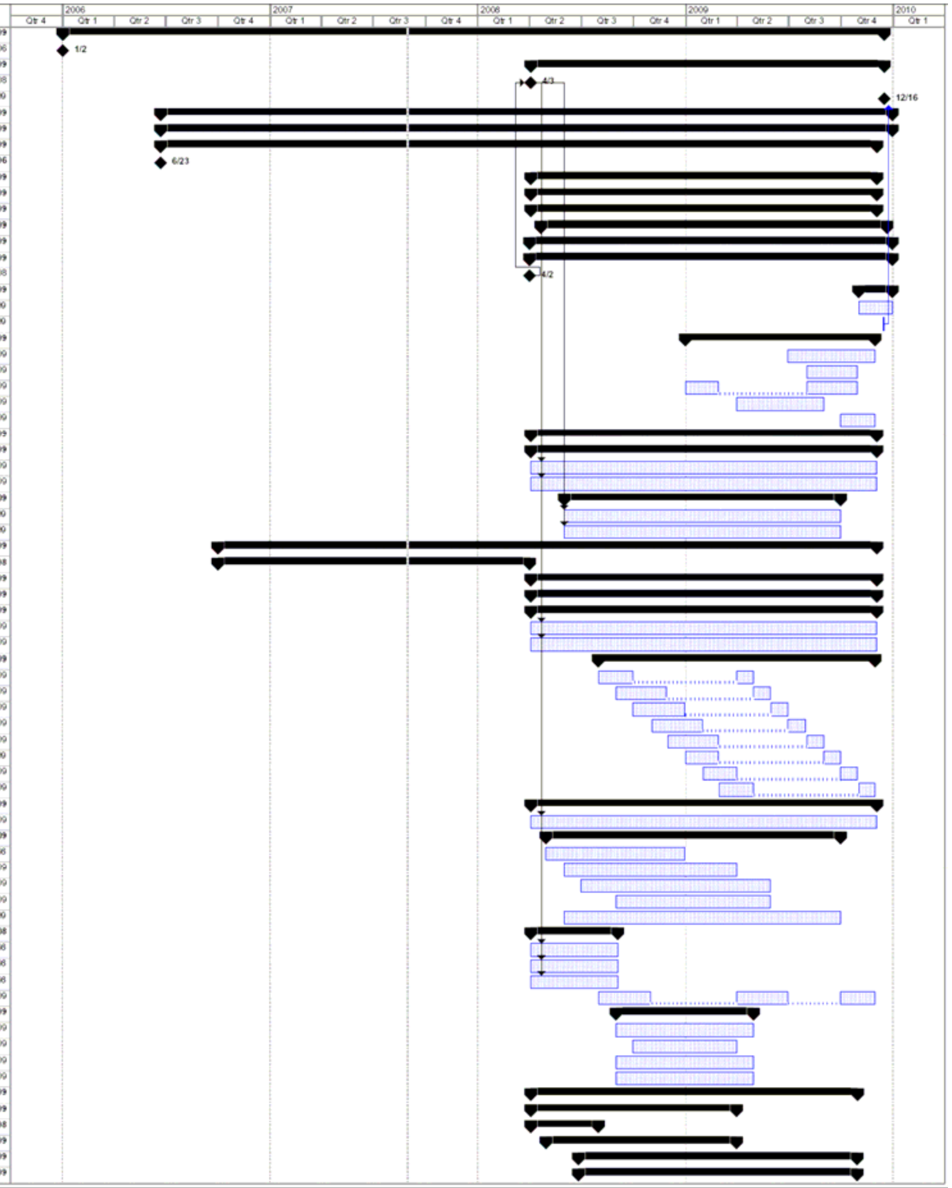


Figure 18: NGAO WBS

ID	WBS	Task Name	Work	Duration	Start	Finish
1	**0**	**NGAO AO System Preliminary Design Phase Milestones**	**0 hrs**	**1033 days**	**Mon 1/2/06**	**Wed 12/16/09**
2	0.1	Project Start	0 hrs	0 days	Mon 1/2/06	Mon 1/2/06
3	**0.2**	**AO System Design Reviews**	**0 hrs**	**444 days**	**Thu 4/3/08**	**Wed 12/16/09**
4	0.2.1	System Design Review	0 hrs	0 days	Thu 4/3/08	Thu 4/3/08
5	0.2.2	Preliminary Design Review	0 hrs	0 days	Wed 12/16/09	Wed 12/16/09
6	**1**	**NGAO Project**	**24,050 hrs**	**919 days**	**Fri 6/23/06**	**Wed 12/30/09**
7	**1.1**	**Management**	**4,370 hrs**	**919 days**	**Fri 6/23/06**	**Wed 12/30/09**
8	**1.1.1**	**Project Management**	**2,200 hrs**	**900 days**	**Fri 6/23/06**	**Thu 12/3/09**
9	**1.1.1.1**	**Proposal**	**0 hrs**	**0 days**	**Fri 6/23/06**	**Fri 6/23/06**
11	**1.1.1.2**	**Programmatic Risk Assessment & Mitigation**	**400 hrs**	**435 days**	**Fri 4/4/08**	**Thu 12/3/09**
15	**1.1.1.3**	**Project Meetings**	**1,600 hrs**	**435 days**	**Fri 4/4/08**	**Thu 12/3/09**
17	**1.1.1.4**	**Schedule and Budget Maintenance**	**200 hrs**	**435 days**	**Fri 4/4/08**	**Thu 12/3/09**
20	**1.1.2**	**Reporting**	**290 hrs**	**435 days**	**Tue 4/22/08**	**Mon 12/21/09**
23	**1.1.3**	**Reviews**	**380 hrs**	**456 days**	**Wed 4/2/08**	**Wed 12/30/09**
24	**1.1.3.1**	**AO Design Reviews**	**380 hrs**	**456 days**	**Wed 4/2/08**	**Wed 12/30/09**
25	1.1.3.1.1	System Design Review	0 hrs	2 days	Wed 4/2/08	Thu 4/3/08
26	**1.1.3.1.2**	**Preliminary Design Review**	**380 hrs**	**43 days**	**Mon 11/2/09**	**Wed 12/30/09**
27	1.1.3.1.2.1	Preliminary Design Review Support	300 hrs	43 days	Mon 11/2/09	Wed 12/30/09
28	1.1.3.1.2.2	Preliminary Design Review	80 hrs	2 days	Tue 12/15/09	Wed 12/16/09
29	**1.1.4**	**Systems Engineering Management Plan**	**1,500 hrs**	**238 days**	**Thu 1/1/09**	**Mon 11/30/09**
30	1.1.4.1	Project Plan	640 hrs	109 days	Wed 7/1/09	Mon 11/30/09
31	1.1.4.2	Risk Assessment & Management Plan	100 hrs	65 days	Mon 8/3/09	Fri 10/30/09
32	1.1.4.3	Detailed Design Phase Plan	260 hrs	107 days	Thu 1/1/09	Fri 10/30/09
33	1.1.4.4	Integration and Test Plans	300 hrs	109 days	Wed 4/1/09	Mon 8/31/09
34	1.1.4.5	SEMP Document	200 hrs	43 days	Thu 10/1/09	Mon 11/30/09
35	**1.2**	**Science**	**2,560 hrs**	**435 days**	**Fri 4/4/08**	**Thu 12/3/09**
36	**1.2.1**	**Science Requirements**	**760 hrs**	**435 days**	**Fri 4/4/08**	**Thu 12/3/09**
37	1.2.1.1	Science Requirements	380 hrs	435 days	Fri 4/4/08	Thu 12/3/09
38	1.2.1.2	Science Case Development	380 hrs	435 days	Fri 4/4/08	Thu 12/3/09
39	**1.2.2**	**Science Operations**	**1,800 hrs**	**348 days**	**Mon 6/2/08**	**Wed 9/30/09**
40	1.2.2.1	Astronomical Observations Operations	800 hrs	348 days	Mon 6/2/08	Wed 9/30/09
41	1.2.2.2	AO-Instrument Operations	1,000 hrs	348 days	Mon 6/2/08	Wed 9/30/09
42	**1.3**	**AO Design**	**17,120 hrs**	**829 days**	**Mon 10/2/06**	**Thu 12/3/09**
43	**1.3.1**	**System Design**	**0 hrs**	**392 days**	**Mon 10/2/06**	**Tue 4/1/08**
45	**1.3.2**	**Preliminary Design**	**17,120 hrs**	**435 days**	**Fri 4/4/08**	**Thu 12/3/09**
46	**1.3.2.1**	**Systems Engineering**	**6,210 hrs**	**435 days**	**Fri 4/4/08**	**Thu 12/3/09**
47	**1.3.2.1.1**	**Requirements**	**670 hrs**	**435 days**	**Fri 4/4/08**	**Thu 12/3/09**
48	1.3.2.1.1.1	System Requirements	170 hrs	435 days	Fri 4/4/08	Thu 12/3/09
49	1.3.2.1.1.2	Functional Requirements	500 hrs	435 days	Fri 4/4/08	Thu 12/3/09
50	**1.3.2.1.4**	**Performance Budgets**	**1,600 hrs**	**347 days**	**Fri 8/1/08**	**Mon 11/30/09**
51	1.3.2.1.4.1	Throughput & Background	100 hrs	65 days	Fri 8/1/08	Thu 4/30/09
52	1.3.2.1.4.2	Wavefront & Encircled Energy	300 hrs	86 days	Mon 9/1/08	Fri 5/29/09
53	1.3.2.1.4.3	Astrometric	300 hrs	88 days	Wed 10/1/08	Tue 6/30/09
54	1.3.2.1.4.4	Photometric	300 hrs	88 days	Mon 11/3/08	Fri 7/31/09
55	1.3.2.1.4.5	Companion Sensitivity	250 hrs	86 days	Mon 12/1/08	Mon 8/31/09
56	1.3.2.1.4.6	Polarimetry	50 hrs	64 days	Thu 1/1/09	Wed 9/30/09
57	1.3.2.1.4.7	Observing Efficiency	150 hrs	64 days	Mon 2/2/09	Fri 10/30/09
58	1.3.2.1.4.8	Observing Uptime	150 hrs	65 days	Mon 3/2/09	Mon 11/30/09
59	**1.3.2.1.5**	**Technical Risk Assessment & Mitigation**	**2,500 hrs**	**435 days**	**Fri 4/4/08**	**Thu 12/3/09**
60	1.3.2.1.5.1	Risk Assessment	200 hrs	435 days	Fri 4/4/08	Thu 12/3/09
61	**1.3.2.1.5.2**	**Risk Mitigation Efforts**	**2,300 hrs**	**370 days**	**Thu 5/1/08**	**Wed 9/30/09**
62	1.3.2.1.5.2.1	CCID-56	500 hrs	175 days	Thu 5/1/08	Wed 12/31/08
63	1.3.2.1.5.2.2	Atmospheric Profiler	500 hrs	217 days	Mon 6/2/08	Tue 3/31/09
64	1.3.2.1.5.2.3	Single Laser Tomography	500 hrs	239 days	Tue 7/1/08	Fri 5/29/09
65	1.3.2.1.5.2.4	Tip/Tilt Vibration Analysis	500 hrs	195 days	Mon 9/1/08	Fri 5/29/09
66	1.3.2.1.5.2.5	Other	300 hrs	348 days	Mon 6/2/08	Wed 9/30/09
67	**1.3.2.1.6**	**System Architecture**	**1,040 hrs**	**109 days**	**Fri 4/4/08**	**Wed 9/3/08**
68	1.3.2.1.6.1	Opto-Mechanical Architecture	400 hrs	109 days	Fri 4/4/08	Wed 9/3/08
69	1.3.2.1.6.2	Software Architecture	360 hrs	109 days	Fri 4/4/08	Wed 9/3/08
70	1.3.2.1.6.3	Motion Control / Electronics Architecture	280 hrs	109 days	Fri 4/4/08	Wed 9/3/08
71	1.3.2.1.7	System Design Manual	400 hrs	174 days	Fri 8/1/08	Mon 11/30/09
72	**1.3.2.2**	**AO Facility Design**	**7,000 hrs**	**174 days**	**Mon 9/1/08**	**Thu 4/30/09**
73	1.3.2.2.1	Opto-mechanical Subsystem	3,200 hrs	174 days	Mon 9/1/08	Thu 4/30/09
74	1.3.2.2.4	AO Enclosure	600 hrs	130 days	Wed 10/1/08	Tue 3/31/09
75	1.3.2.2.5	Real-time Control	2,000 hrs	174 days	Mon 9/1/08	Thu 4/30/09
76	1.3.2.2.6	Other Controls	1,200 hrs	174 days	Mon 9/1/08	Thu 4/30/09
77	**1.3.2.3**	**Laser Facility Design**	**3,300 hrs**	**411 days**	**Fri 4/4/08**	**Fri 10/30/09**
85	**1.3.2.4**	**External Interfaces**	**610 hrs**	**258 days**	**Fri 4/4/08**	**Tue 3/31/09**
86	**1.3.2.4.1**	**Observatory Interfaces**	**220 hrs**	**85 days**	**Fri 4/4/08**	**Thu 7/31/08**
89	**1.3.2.4.2**	**Instrument Interfaces**	**390 hrs**	**239 days**	**Thu 5/1/08**	**Tue 3/31/09**
98	**1.4**	**Instrumentation Design**	**0 hrs**	**350 days**	**Fri 6/27/08**	**Thu 10/29/09**
99	**1.4.1**	**System Design**	**0 hrs**	**350 days**	**Fri 6/27/08**	**Thu 10/29/09**



Page 1

Figure 19: NGAO preliminary design phase schedule

5. BUDGET

This proposal to TSIP is for the preliminary design phase (i.e. part of TSIP phases A and B) of the AO component of the NGAO system. We propose the exchange of 20 observing nights (starting in semester 2008B) for funding of $2,047,360 over 2 years. Design and construction of the AO component of NGAO system will be through collaboration among WMKO, the UCSC and CIT. Industrial partners will also be part of the project, particularly for the laser facility and the DMs.

5.1. Overall Project Budget

The overall project budget is shown in Figure 20. The total cost to completion is currently estimated at $35,000,000 with a contingency of $8,568,087 for a total of $43,568,087. This includes labor costs of $17,728,559 and equipment and materials costs of $16,720,682. These are preliminary estimates and will continue to be refined as the system design phase of the project continues. Not included in this budget is the cost of instrumentation, this is currently estimated at $20,000,000 for the multi-object deployable IFU and the visible and near-IR imagers.

The estimated cost to completion includes all of the required interfaces and facilities modifications at the Observatory. 4% allowance for inflation is applied to labor costs in years 3 through 8 of the project.

At this time, we are carrying a contingency estimate of 10% for labor during the preliminary and detailed design phases, and 30% for the remaining project phases. We are also carrying a contingency of 30% for the equipment and materials costs during the full scale development phase of the project. These contingency amounts will be refined as the project progresses, and we expect them to fall to the 15% level by the completion of the detailed design phase.

It should be noted that none of the collaborating organizations are applying their normal indirect cost rates to the project.

5.2. System Design Phase

The system design phase, currently underway, is entirely funded by WMKO at a cost of $1,200,000.

5.3. Preliminary Design Phase

The preliminary design phase budget is shown in Figure 21. The total cost for this phase is estimated at $2,700,000 not including contingency. This includes $400,000 for equipment to be used in the prototyping of the near-IR tip-tilt sensor and $200,000 for testing and subcontracts related to the MOAO implementation. An equipment cost breakdown in shown in Table 12. $150,000 is also included for travel costs related to project meetings and collaborative work activities. 4% allowance for inflation is applied to labor costs in years 3 and 4. There is also a contingency allowance of 10% for labor in this project phase.

Item	**Est. Cost**	
2 Near-IR detectors	$	185,000
Readout system	$	45,000
MEMS DM and controller	$	58,000
Real time computer	$	15,000
Cryostat	$	35,000
Optics	$	22,000
Misc. components	$	16,000
Test sources and optics	$	24,000
Total	$	400,000

Table 12: Preliminary design phase equipment budget

5.4. Funding Plans

The overall project budget shown in Figure 20 includes a funding profile for this project. As indicated substantial private funding is required to complete NGAO. The Observatory has an active fund raising effort underway through its advancement office and NGAO is a top priority in this activity.

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

August 31, 2007

Expenses	Notes	Person Months	Year 1 FY07	Year 2 FY08	Year 3 FY09	Year 4 FY10	Year 5 FY11	Year 6 FY12	Year 7 FY13	Year 8 FY14	Total for Project
Senior Personnel											
Peter Wizinowich, Principal Investigator	1	43	$ 97,980	$ 99,940	$ 105,975	$ 110,214	$ 114,623	$ 119,208	$ 123,976	$ 21,489	$ 793,404
Claire Max, Project Scientist	2	43	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Richard Dekany, Co-investigator	1	43	$ 97,980	$ 99,940	$ 105,975	$ 110,214	$ 114,623	$ 119,208	$ 123,976	$ 21,489	$ 793,404
Donald Gavel, Co-investigator	1	43	$ 97,980	$ 99,940	$ 105,975	$ 110,214	$ 114,623	$ 119,208	$ 123,976	$ 21,489	$ 793,404
Total Senior Personnel		172	$ 293,940	$ 299,819	$ 317,926	$ 330,643	$ 343,868	$ 357,623	$ 371,928	$ 64,467	$ 2,380,213
Other Personnel											
Post Doctoral Associates		0	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Other Professionals (Technician, Programmer, Etc.)	1	1006	$ 315,435	$ 336,108	$ 543,525	$ 2,760,328	$ 2,131,383	$ 1,716,926	$ 2,394,138	$ 1,073,720	$ 11,271,563
Graduate Students			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Undergraduate Students			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Secretarial - Clerical (If Charged Directly)			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Other			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Total Salaries and Wages			$ 609,375	$ 635,927	$ 861,451	$ 3,090,970	$ 2,475,251	$ 2,074,549	$ 2,766,066	$ 1,138,187	$ 13,651,777
Fringe Benefits	3		$ 170,625	$ 184,216	$ 258,435	$ 927,291	$ 742,575	$ 622,365	$ 829,820	$ 341,456	$ 4,076,783
Total Salaries, Wages and Fringe Benefits			$ 780,000	$ 820,143	$ 1,119,886	$ 4,018,261	$ 3,217,826	$ 2,696,914	$ 3,595,886	$ 1,479,643	$ 17,728,559
Equipment			$ -	$ -	$ 400,000	$ -	$ 4,366,342	$ 5,874,745	$ 5,016,585	$ -	$ 15,657,671
Travel											
Domestic			$ -	$ 42,857	$ 85,714	$ 93,139	$ 99,438	$ 103,415	$ 107,552	$ 18,642	$ 550,758
Foreign			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Other Direct Costs											
Materials and Supplies			$ -	$ -	$ -	$ -	$ 278,680	$ 314,640	$ 269,691	$ -	$ 863,011
Publication Costs/Documentation/Dissemination			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Consultant Services			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Computer Services			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Subawards (Subcontracts)			$ -	$ -	$ 200,000	$ -	$ -	$ -	$ -	$ -	$ 200,000
Other			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Total Other Direct Costs			$ -	$ -	$ 200,000	$ -	$ 278,680	$ 314,640	$ 269,691	$ -	$ 1,063,011
Total Direct Costs			$ 780,000	$ 863,000	$ 1,805,600	$ 4,111,400	$ 7,962,286	$ 8,989,714	$ 8,989,714	$ 1,498,286	$ 35,000,000
Indirect Costs	4		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Total Indirect Costs			$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Total Direct and Indirect Costs			$ 780,000	$ 863,000	$ 1,805,600	$ 4,111,400	$ 7,962,286	$ 8,989,714	$ 8,989,714	$ 1,498,286	$ 35,000,000

Contingency	Notes	Rate	Year 1 FY07	Year 2 FY08	Year 3 FY09	Year 4 FY10	Year 5 FY11	Year 6 FY12	Year 7 FY13	Year 8 FY14	Total for Project
Labor (Total Salaries, Wages and Fringe Benefits)	5	10%, 30%	$ 78,000	$ 82,014	$ 111,989	$ 401,826	$ 726,320	$ 809,074	$ 1,078,766	$ 443,893	$ 3,731,882
Materials (Equipment, Materials and Supplies)	6	30%	$ -	$ -	$ -	$ -	$ 1,393,506	$ 1,856,815	$ 1,585,883	$ -	$ 4,836,205
Less Planned Usage of Contingency	7		$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -	$ -
Total Contingency			$ 78,000	$ 82,014	$ 111,989	$ 401,826	$ 2,119,826	$ 2,665,890	$ 2,664,649	$ 443,893	$ 8,568,087
Total Cost including contingency			$ 858,000	$ 945,014	$ 1,917,589	$ 4,513,226	$ 10,082,112	$ 11,655,604	$ 11,654,363	$ 1,942,179	$ 43,568,087

Funding Profile	Notes		Year 1 FY07	Year 2 FY08	Year 3 FY09	Year 4 FY10	Year 5 FY11	Year 6 FY12	Year 7 FY13	Year 8 FY14	Total for Project
Projected TSIP Funding	8			$ 1,023,680	$ 1,023,680	$ 2,456,832	$ 2,456,832	$ 2,456,832	$ 2,456,832	$ 2,456,832	$ 14,331,520
Observatory Operations Funding			$ 780,000	$ 420,000	$ 750,000	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 1,000,000	$ 6,170,000
Private Funding	9		$ -	$ 150,000	$ 1,500,000	$ 3,000,000	$ 3,500,000	$ 5,000,000	$ 5,000,000	$ 5,000,000	$ 23,150,000
Total Funding			$ 780,000	$ 1,593,680	$ 3,273,680	$ 6,456,832	$ 6,956,832	$ 8,456,832	$ 8,456,832	$ 8,456,832	$ 43,651,520

Notes:
1. Inflation allowed for labor costs at 4% per year for years 3 through 8.
2. Academic appointment, no direct labor charged to project.
3. Benefits in rate is 30%.
4. All participants are waiving their normal indirect cost charges.
5. Labor contingency is 10% on PD and DD phases, and 30% for balance of project.
6. Materials contingency is 30% for detailed design phase to completion.
7. No usage of contingency is planned at this time.
8. 10 nights per year in years 2 and 3, then 24 nights per year starting in FY10.
9. Private funding sources TBD.

Figure 20: Full project budget

Expenses	**Notes**	**Person Months**	**Project Year 2 FY08**	**Project Year 3 FY09**	**Project Year 4 FY10**	**Total for Preliminary Design**
Senior Personnel						
Peter Wizinowich, Principal Investigator	1	11	$ 50,950	$ 105,975	$ 27,554	$ 184,478
Claire Max, Project Scientist	2	11	$ -	$ -	$ -	$ -
Richard Dekany, Co-investigator	1	11	$ 50,950	$ 105,975	$ 27,554	$ 184,478
Donald Gavel, Co-investigator	1	11	$ 50,950	$ 105,975	$ 27,554	$ 184,478
Total Senior Personnel		42	$ 152,849	$ 317,926	$ 82,661	$ 553,435
Other Personnel						
Post Doctoral Associates		0	$ -	$ -	$ -	$ -
Other Professionals (Technician, Programmer, Etc.)	1	85	$ 154,953	$ 543,525	$ 248,087	$ 946,565
Graduate Students			$ -	$ -	$ -	$ -
Undergraduate Students			$ -	$ -	$ -	$ -
Secretarial - Clerical (If Charged Directly)			$ -	$ -	$ -	$ -
Other			$ -	$ -	$ -	$ -
Total Salaries and Wages			$ 307,802	$ 861,451	$ 330,747	$ 1,500,000
Fringe Benefits	3		$ 92,341	$ 258,435	$ 99,224	$ 450,000
Total Salaries, Wages and Fringe Benefits			$ 400,143	$ 1,119,886	$ 429,971	$ 1,950,000
Equipment			$ -	$ 400,000	$ -	$ 400,000
Travel						
Domestic			$ 42,857	$ 85,714	$ 21,429	$ 150,000
Foreign			$ -	$ -	$ -	$ -
Other Direct Costs						
Materials and Supplies			$ -	$ -	$ -	$ -
Publication Costs/Documentation/Dissemination			$ -	$ -	$ -	$ -
Consultant Services			$ -	$ -	$ -	$ -
Computer Services			$ -	$ -	$ -	$ -
Subawards (Subcontracts)			$ -	$ 200,000	$ -	$ 200,000
Other			$ -	$ -	$ -	$ -
Total Other Direct Costs			$ -	$ 200,000	$ -	$ 200,000
Total Direct Costs			$ 443,000	$ 1,805,600	$ 451,400	$ 2,700,000
Indirect Costs	4		$ -	$ -	$ -	$ -
Total Indirect Costs			$ -	$ -	$ -	$ -
Total Direct and Indirect Costs			$ 443,000	$ 1,805,600	$ 451,400	$ 2,700,000
Contingency		**Rate**				
Labor (Total Salaries, Wages and Fringe Benefits)	5	10%	$ 40,014	$ 111,989	$ 42,997	$ 195,000
Materials (Equipment, Materials and Supplies)	6	0%	$ -	$ -	$ -	$ -
Less Planned Usage of Contingency	7		$ -	$ -	$ -	$ -
Total Contingency			$ 40,014	$ 111,989	$ 42,997	$ 195,000
Total Cost including contingency			$ 483,014	$ 1,917,589	$ 494,397	$ 2,895,000
Funding Profile						
Projected TSIP Funding	8		$ 1,023,680	$ 1,023,680		$ 2,047,360
Observatory Operations Funding			$ 420,000	$ 127,640		$ 547,640
Private Funding	9		$ 150,000	$ 150,000		$ 300,000
Total Funding			$ 1,593,680	$ 1,301,320	$ -	$ 2,895,000

Notes:
1. Inflation allowed for labor costs at 4% per year for years 3 through 8.
2. Academic appointment, no direct labor charged to project.
3. Benefits in rate is 30%.
4. All participants are waiving their normal indirect cost charges.
5. Labor contingency is 10% for the preliminary design phase.
6. No materials contingency for this phase.
7. No usage of contingency is planned at this time.
8. 10 nights per year in years 2 and 3.
9. Private funding sources TBD.

Figure 21: Preliminary design phase budget

6. COMMUNITY ACCESS

6.1. Introduction

In exchange for the funding of the preliminary design phase (i.e. part of TSIP phases A and B) of the AO component of the NGAO system, WMKO will provide observing time on its telescopes. One of the great strengths of this proposal is that the Observatory offers immediate community access to a broad range of well-proven instrumentation on working 10 meter telescopes. The complete instrument suite on both telescopes, which will be available to the observers that are granted time in this exchange, includes:

<u>*Keck I*</u>

- **LRIS** *(Keck I – Cassegrain focus) – Low Resolution Imager / Spectrograph*
  310 to 1000 nm dual-beam spectrometer / imager. Long slit and multi-slit (up to 30 objects) with R = 300 to 5,000. Imaging over a 6' x 8' field. A Tektronix 2k x 2k, 24 µm pixel detector on the red arm and a mosaic of two 2k x 4k, 15 µm pixel E2V detectors on the blue arm.
  An atmospheric dispersion corrector is now a standard Cassegrain facility for use with LRIS.

  - Work is underway to design and build an upgrade to the red arm detector system.

- **HIRES** *(Keck I – right Nasmyth focus) – High Resolution Echelle Spectrometer*
  350 to 1000 nm Echelle spectrograph; R = 30,000 to 80,000. 4k x 6k detector, consisting of a mosaic of three 2k x 4k, 15 µm pixel MIT/LL CCDs

- **NIRC** *(Keck I – Cassegrain focus) – Near Infrared Camera*
  1 to 5 µm imaging (38" field) and R=100 spectroscopy. Hughes/SBRC 256 x 256 InSb detector.

<u>*Keck II*</u>

- **ESI** *(Keck II – Cassegrain focus) – Echellette Spectrograph and Imager*
  390 to 1100 nm imager (to 2' x 8' field) and spectrograph (R = 1,000 to 32,000).
  2k x 4k MIT/LL CCD detector.

- **NIRSPEC** *(Keck II –Nasmyth focus/AO option) – Near Infrared Spectrometer*
  0.95 to 5.5 µm spectroscopy (R=2,500 and R=25,000) with Aladdin 1k x 1k InSb detector, and 1 to 2.5 µm imaging (46" field) with Rockwell HgCdTe 256 x 256 detector.

- **DEIMOS** *(Keck II – right Nasmyth focus) – Deep Extragalactic Imaging and Multi-Object Spectrograph. 390 to 1100 nm imaging (17' x 5' field) and R=6,000 spectroscopy on up to 85 objects simultaneously. Eight 2k x 4k MIT/LL CCD detectors.*

- **Adaptive Optics** *(Keck II – left Nasmyth focus)*
  Natural guide star AO system (same as Keck I AO), used with NIRC2 and NIRSPEC.

- **LGS** *(Keck II) – Laser Guide Star*
  12 watt (projected power) 589 nm laser to produce a 9^{th} magnitude reference for Keck II AO system. LGS AO is used with NIRSPEC, NIRC2 and OSIRIS.

- **NIRC2** *(Keck II – Nasmyth focus on side port of AO system) – Near Infrared Camera 2*
  1 to 5 µm high resolution imager (0.01" to 0.04" pixel scale, 10" to 40" field) and R=5,000 spectrograph - permanently mounted at Keck II AO. Aladdin 1k x 1k InSb detector.

- **OSIRIS** *(Keck II – Nasmyth focus, AO system) – OH-Suppressing Infra-Red Imaging Spectrograph*
  Near-IR integral field spectrograph (0.9 µm to 2.5 µm) using a focal plane lenslet array (64 x 64 lenslets) to create an integral field spectrograph capable of simultaneous diffraction-limited

imaging and R=3,900 spectroscopy behind the Keck II AO system. Four plate scales from 0.02" to 0.1" with fields of view up to 1.6" x 6.4" in broad band mode (z, J, H, K) using a 2k x 2k Hawaii-2 HgCdTe array. A separate imager provides a 20" x 20" field of view using a 1k x 1k Hawaii-1 HgCdTe array.

<u>*Instrumentation in development*</u>

- **MOSFIRE** *(Keck I – Cassegrain focus) – Multi-Object Spectrometer for Infra-Red Exploration*
  A cryogenic multi-object near-infrared spectrometer providing near-IR (~0.9 to 2.5 μm) multi-object spectroscopy over a 6.1' x 3' field of view with a resolving power of R~3,300 for a 0.7" slit width (R~4,600 for a 0.5" slit), or imaging over a field of view of 6.14' x 6.14' with 0.18" per pixel sampling with a 2k x 2k Hawaii-2RG detector. A special feature of MOSFIRE is that its multiplex advantage of up to 46 slits is achieved using a cryogenic slit unit that is reconfigurable under remote control in less than 5 minutes without any thermal cycling of the instrument..

- **LGS** *(Keck I) – Laser Guide Star*
  20 watt solid state 589 nm laser for the Keck I AO system.
  Currently plans are to relocate OSIRIS to Keck I for use with this new LGS AO capability.

- **Interferometer** *(Keck I and Keck II)*
  Visibility measurements to K=14, nulling to detect exozodiacal dust.

  - This capability is still in development. This capability is offered on a shared risk basis to the general community contingent on continued NASA support to WMKO for interferometer operations

6.2. Scheduling of Community Access

WMKO allocates observing time twice per year, for six month periods: semester A (February - July) and semester B (August - January). Telescope time is allocated by five Telescope Allocation Committees (TACs), from U. California, CIT, NASA, U. Hawaii, and the NSF TAC for TSIP observing. Prior to the call for proposals, WMKO defines the number of telescope nights that will be allocated by each TAC, taking into account the need for engineering nights. After each TAC awards telescope time, WMKO combines the requests into a schedule that minimizes instrument exchanges and takes into account special requirements (engineering time, commissioning, and time-critical observations). There is substantial iteration between WMKO and the TACs to ensure that all parties are mutually satisfied.

6.3. Exchange of telescope time

For this proposal, we are requesting funding of $2,047,360. We have computed the value of Keck telescope time at $51,184 per telescope per night. With the TSIP instrument development exchange rate of two, we propose 20 observing nights in exchange for the funds. Telescope nights will be provided during 4 semesters starting in 2008B.

6.4. Computation of the Cost of a Night of Keck Telescope Observing

The value of one night of observing with one of the Keck 10 meter telescopes is derived from two numbers; total annual cost of the WMKO facility divided by the number of nights the telescopes are used for observations by the Observatory partners.

Cost per night = (Annual cost) / (Number of nights telescopes used by partners)

The annual cost is a combination of three cost areas:

- Amortized observatory development
- Amortized instrument development
- Annual operations cost

This proposal for the preliminary design of the AO component of the NGAO system is for a period of 21 months over the FY08 to FY10 budget years. We have included the new capabilities for which we have committed funds through FY09. The WMKO fiscal year matches the federal fiscal year. The annual cost is computed using the following rules:

- Observatory development costs are linearly amortized over 20 years.
- Instrumentation costs are linearly amortized over 10 years.
- The costs for capabilities that will be commissioned by FY09 are included. Costs for capabilities that are in development or not in use are not included.
- The costs are in "then year" dollars (no inflation factor used), with the exception of the operation funds, as stated below.
- The cost of capabilities is weighted as a function of time. We have retained the weighting used in our previous proposal using increments of 20% as follows. Capabilities completed by end of FY04 are weighted 100%; those completed by end of FY05 are weighted 80%. For completion in FY06-09, the weighted values of capabilities are respectively 60%, 40%, 20% and 0%.
- The annual operation cost is the amount of funds provided annually by the Observatory partners. We have used the FY04 budgeted value and adjusted it by 9.7% due to the average expected inflation rate of 3.1% over the next 5 years.

The total weighted development cost for the Keck observatory is $189.6 million.

The total development cost for the single aperture instruments is $61.1 million:

Keck I: Adaptive Optics, HIRES, LRIS, LWS, NIRC, ADC, NIRES

Keck II: Adaptive Optics, DEIMOS, ESI, NIRC2, NIRSPEC, OSIRIS

The annual operations funds come from contributions by the University of California and NASA. In FY04, these funds were $12.20 million. Increasing by 9.7%, the average operations funds during the period of this TSIP contract will be $13.38 million. Combining these figures, the total annual costs for the Observatory are computed (figures are in millions of dollars).

Cost area	Total Cost ($ million)	Annual Cost ($ million)
Observatory development	189.6	9.48
Instrumentation	61.1	6.11
Annual Operations		13.38
W. M. Keck Observatory total annual cost		**28.97**

The number of observing nights available to the Observatory partners is the time remaining after subtracting engineering time and University of Hawaii observing time. The telescope time will be exchanged with TSIP during FY08 to FY10, and we expect the average allocation of nights to be as shown in the table below.

Total number of nights / both telescopes	730
Telescope engineering time	-53
University of Hawaii observing time	-85
Instrument engineering time	-26
Number of nights available for allocation to the three observatory partners	566

With 566 nights available for observing, the weighted value of one observing night on a Keck telescope is $51,184.

6.5. Cost of W. M. Keck Observatory nights for TSIP

WMKO is proposing a contribution of 10 telescope nights per year for 2 years in exchange for funds to be used for the preliminary design phase (i.e. part of TSIP phases A and B) of the AO component of the NGAO system. Using the exchange factor of 2 for instrumentation development and a value of one observing night of $51,184, the exchange of these 20 observing nights is valued at $2,047,360.

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8. APPENDICES

8.1. Technical Requirements

The first two columns list the science requirements from Table 5, and the remaining columns show how these requirements are flowed down to the key NGAO technical performance and implementation requirements.

Science Requirement	Value(s)	Derived Technical Requirement	Parameter values and/or implementation details	Notes
Parameter space				
Wavelength range	0.7 to 1.0 μm 0.9 to 2.45 μm	Beam splitting for LGS WFS		
		Cut-on wavelength	595 nm	
		Passband transmission	≥ 95%	
		Cut-off wavelength	585 nm	
		Selectable wavelength pick-off/beam splitting for tip-tilt stars	Multiple filters required to support observing in different near-IR bands	Near-IR light shared with deployable IFU science field
Sensitivity	0.7 to 1.0 μm 0.9 to 2.45 μm	Telescope+AO system transmission	≥ 60% from 0.7 to 1.0 μm	Same optical path as near-IR is assumed
		Telescope+AO system transmission	≥ 60% from 0.9 to 2.45 μm	Background and sensitivity requirements strictest for K band observations
		Strehl(λ)	> 0.6	Diffraction limited at all wavelengths
		Instrument characteristics		
		Instrument transmission		
		Imaging	>60% from 0.7 to 1.0 μm >60% from 0.9 to 2.45 μm	
		Spectroscopy	>40% from 0.7 to 1.0 μm >40% from 0.9 to 2.45 μm	
		Spatial sampling	Nyquist at short wavelength cut-off: 0.7 μm = 6 mas 0.9 μm = 10 mas	Determines number of pixels in the photometric aperture
		Detector QE	≥ 85%	
		Detector noise	≤ 10 e^-/pixel/read	
		Instrument background	<0.001 e^-/pixel/s	

Table 13: NGAO technical requirements summary

Science Requirement	**Value(s)**	**Derived Technical Requirement**	**Parameter values and/or implementation details**	**Notes**
Parameter space				
Wavefront error	140 nm	Tomography		
	170 nm	Multiple LGS beacons	9 beacons, 6 in variable radius constellation from 11" to 90", 3 free ranging with 101" radius	
		Multiple LGS WFS	9 low noise SH wavefront sensors, 202" diameter field accessible to LGS WFS.	
		Multiple near-IR tip-tilt stars	3 MOAO sharpened tip-tilt sensors	At least one tip-tilt, focus and astigmatism sensor
		High order correction (large # actuators)	20 x 20 low order DM	
			64 x 64 high order DM in narrow field relay	
	200 nm		32 x 32 high order DM in each multi-object instrument head	Meets ensquared energy for 50 to 100 mas spatial sampling for spatially resolved spectroscopy
Field of view	~2" ≤ 3" 5" ≥10" ≤ 20"	Narrow field AO relay Variable size LGS asterism Technical field of regard MOAO correction of tip-tilt stars Multiple LGS beacons	30" diameter 180" diameter	
	1" x 3", ≥ 6 fields over 120" field of regard	MOAO correction in each head of the multi-object deployable IFU	OSM accesses 120"diameter field	
Background	≤ 20% over the unattenuated sky+telescope background	Control of scattered light	<1% total contribution to AO system background	
		Cooling of AO system	260 K	
		Cold stop(s)	Matched to telescope pupil, rotating, hexagonal shape	Most important for K band
		Instrument characteristics		
		Instrument background	<0.001 e^-/pixel/s	
Contrast	ΔJ=11at 0.2" separation	Coronagraph	6λ/D occulting spot diameter with apodized Lyot stop (rotating, hexagonal shape)	
		Calibrate non-static, non-common path aberrations		
		Servo lag error	< 1 ms	
		Speckle suppression		Including spatially resolved spectroscopy

Table 13: NGAO technical requirements summary, cont'd.

Science Requirement	Value(s)	Derived Technical Requirement	Parameter values and/or implementation details	Notes
Performance				
	ΔH=5.5 at 0.5" separation	N/A	N/A	Achieved by predicted Strehl and PSF morphology
	ΔI=7.5 at 0.75"separation	N/A	N/A	Achieved by predicted Strehl and PSF morphology
Photometric accuracy				
Absolute	≤ 0.05 magnitudes	PSF stability		
		PSF calibration	Precise PSF knowledge	
		PSF monitoring	Nyquist sampled PSF imager in observation wavelength band	
			Deployable over technical field of view	
		C_n^2 monitoring facility	Real time turbulence data	
		Deconvolution pipeline software		
		Instrument characteristics		
		Detector stability		
		Detector linearity		
Relative	≤ 0.01 magnitudes	PSF stability		
	≤ 0.05 magnitudes	PSF calibration	Precise PSF knowledge	
		PSF monitoring	Nyquist sampled PSF imager in observation wavelength band	
			Deployable over technical field of view	
		C_n^2 monitoring facility	Real time turbulence data	
		Deconvolution pipeline software		
		Instrument characteristics		
		Detector stability		
		Detector linearity		
	~0.1 magnitudes	Instrument characteristics		
		Detector stability		
		Detector linearity		

Table 13: NGAO technical requirements summary, cont'd.

Science Requirement	Value(s)	Derived Technical Requirement	Parameter values and/or implementation details	Notes
Performance				
Astrometric precision	100 µas 500 µas	Limit distortion in imaging field of view	≤ 1 mas	
		Calibrate distortion in imaging field of view	≤ 1 mas	
		PSF monitoring	Nyquist sampled PSF imager in observation wavelength band	
			Deployable over technical field of view	
		C_n^2 monitoring facility	Real time turbulence data	
		Atmospheric dispersion corrector		
		Plate scale stability	≤ 1 part in 10^4	
		Wavefront error	≤ 140 nm	
		Mechanical stability		
	1.5 mas 10 mas	Plate scale stability	≤ 1 part in 10^4	As provided by current AO system
Sky coverage	≥ 30% (areal average over all sky)	Multiple near-IR tip-tilt stars	3 MOAO sharpened tip-tilt sensors	
		Tip-tilt stars at least partially AO corrected		
		Technical field of view for TT selection	180" diameter	
Observing modes				
Imaging	Visible			
	Visible with coronagraph			
	Near-IR with coronagraph			
Spectroscopy	Visible			
	Near-IR IFU			
	Near-IR deployable IFU			

Table 13: NGAO technical requirements summary, cont'd.

8.2. Full Project Schedule

ID	WBS	Task Name	Duration	Start	Finish
1	0	**Milestones**	2065 days	Mon 1/2/06	Fri 11/29/13
2	0.1	Project Start	0 days	Mon 1/2/06	Mon 1/2/06
3	0.2	**AO System Design Reviews**	1457 days	Thu 4/3/08	Mon 11/4/13
4	0.2.1	System Design Review	0 days	Thu 4/3/08	Thu 4/3/08
5	0.2.2	Preliminary Design Review	0 days	Wed 12/16/09	Wed 12/16/09
6	0.2.3	Detailed Design	0 days	Thu 12/16/10	Thu 12/16/10
7	0.2.4	Full Scale Development Intermediate Review 1	0 days	Mon 7/11/11	Mon 7/11/11
8	0.2.5	Full Scale Development Intermediate Review 2	0 days	Wed 3/21/12	Wed 3/21/12
9	0.2.6	Pre-ship Review	0 days	Mon 12/3/12	Mon 12/3/12
10	0.2.7	First Light	0 days	Fri 4/5/13	Fri 4/5/13
11	0.2.8	Acceptance Review	0 days	Fri 9/20/13	Fri 9/20/13
12	0.2.9	Operational Readiness Review	0 days	Mon 11/4/13	Mon 11/4/13
13	0.2.10	Science Verification Review	0 days	Fri 11/1/13	Fri 11/1/13
14	0.3	**Laser Facility Design Reviews**	472 days	Wed 12/15/10	Thu 10/4/12
16	0.4	**Instrumentation Design Reviews**	1478 days	Wed 4/2/08	Fri 11/29/13
18	1	NGAO Project	2070 days	Mon 1/2/06	Fri 12/6/13
19	1.1	**Management**	2070 days	Mon 1/2/06	Fri 12/6/13
20	1.1.1	**Project Management**	2070 days	Mon 1/2/06	Fri 12/6/13
21	1.1.1.1	**Proposal**	0 days	Fri 6/23/06	Fri 6/23/06
23	1.1.1.2	**Programattic Risk Assesment and Mitigation**	2070 days	Mon 1/2/06	Fri 12/6/13
27	1.1.1.3	**Project Meetings**	2070 days	Mon 1/2/06	Fri 12/6/13
29	1.1.1.4	**Schedule and Budget Maintenance**	2070 days	Mon 1/2/06	Fri 12/6/13
32	1.1.2	**Reporting**	2070 days	Mon 1/2/06	Fri 12/6/13
34	1.1.3	**Reviews**	1478 days	Wed 4/2/08	Fri 11/29/13
35	1.1.3.1	**AO Design Reviews**	1459 days	Wed 4/2/08	Mon 11/4/13
46	1.1.3.2	**Laser Facility Design Reviews**	472 days	Wed 12/15/10	Thu 10/4/12
48	1.1.3.3	**Instrumentation Design Reviews**	1478 days	Wed 4/2/08	Fri 11/29/13
50	1.1.4	**Systems Engineering Management Plan**	238 days	Thu 1/1/09	Mon 11/30/09
52	1.2	**Science**	1473 days	Mon 1/2/06	Wed 8/24/11
53	1.2.1	**Science Requirements**	1305 days	Mon 1/2/06	Fri 12/31/10
56	1.2.2	**Science Operations**	1278 days	Mon 10/2/06	Wed 8/24/11
59	1.3	**AO Design**	1097 days	Mon 10/2/06	Tue 12/14/10
60	1.3.1	**System Design**	392 days	Mon 10/2/06	Tue 4/1/08
62	1.3.2	**Preliminary Design**	444 days	Wed 4/2/08	Mon 12/14/09
64	1.3.3	**Detailed Design**	261 days	Tue 12/15/09	Tue 12/14/10
66	1.4	**Instrumentation Design**	700 days	Wed 4/2/08	Tue 12/7/10
68	1.5	**AO Full Scale Development**	872 days	Wed 6/30/10	Thu 10/31/13
69	1.5.1	**AO Facility**	512 days	Wed 12/15/10	Thu 11/29/12
76	1.5.2	**Laser Facility**	472 days	Wed 12/15/10	Thu 10/4/12
84	1.5.3	**Operations Tools Development**	392 days	Wed 12/15/10	Thu 6/14/12
89	1.5.4	**External Interfaces**	572 days	Wed 6/30/10	Thu 9/6/12
90	1.5.4.1	**Telescope & Summit Facilities Development**	392 days	Wed 12/15/10	Thu 6/14/12
92	1.5.4.2	**Facilities Preparations for AO System**	315 days	Wed 6/30/10	Tue 9/13/11
97	1.5.4.3	**Facilities Preparations for Laser System**	195 days	Wed 12/15/10	Tue 9/13/11
102	1.5.4.4	**Facilities Preparations for Science Instrument(s)**	195 days	Wed 12/15/10	Tue 9/13/11
104	1.5.4.5	**Telescope & Summit Development Acceptance Ac**	60 days	Fri 6/15/12	Thu 9/6/12
106	1.5.5	**Delivery and Commisioning**	280 days	Fri 10/5/12	Thu 10/31/13
107	1.5.5.1	**Telescope Integration & Test**	280 days	Fri 10/5/12	Thu 10/31/13
108	1.5.5.1.1	AO System Installation	60 days	Fri 11/30/12	Thu 2/21/13
109	1.5.5.1.2	AO System Integration & Test	30 days	Fri 2/22/13	Thu 4/4/13
110	1.5.5.1.3	Laser System Installation	20 days	Fri 10/5/12	Thu 11/1/12
111	1.5.5.1.4	Laser System Integration & Test	20 days	Fri 11/2/12	Thu 11/29/12
112	1.5.5.1.5	Science Instrument Integration & Test with NGAC	60 days	Fri 4/5/13	Thu 6/27/13
113	1.5.5.1.6	On-sky Testing	60 days	Fri 4/5/13	Thu 6/27/13
114	1.5.5.1.7	Performance Characterization	60 days	Fri 6/28/13	Thu 9/19/13
115	1.5.5.1.8	Science Verification	60 days	Fri 8/9/13	Thu 10/31/13
116	1.5.5.1.50	Shared-risk Science Starts	0 days	Thu 9/19/13	Thu 9/19/13
117	1.6	**Instrumentation Full Scale Development**	900 days	Wed 12/23/09	Tue 6/4/13

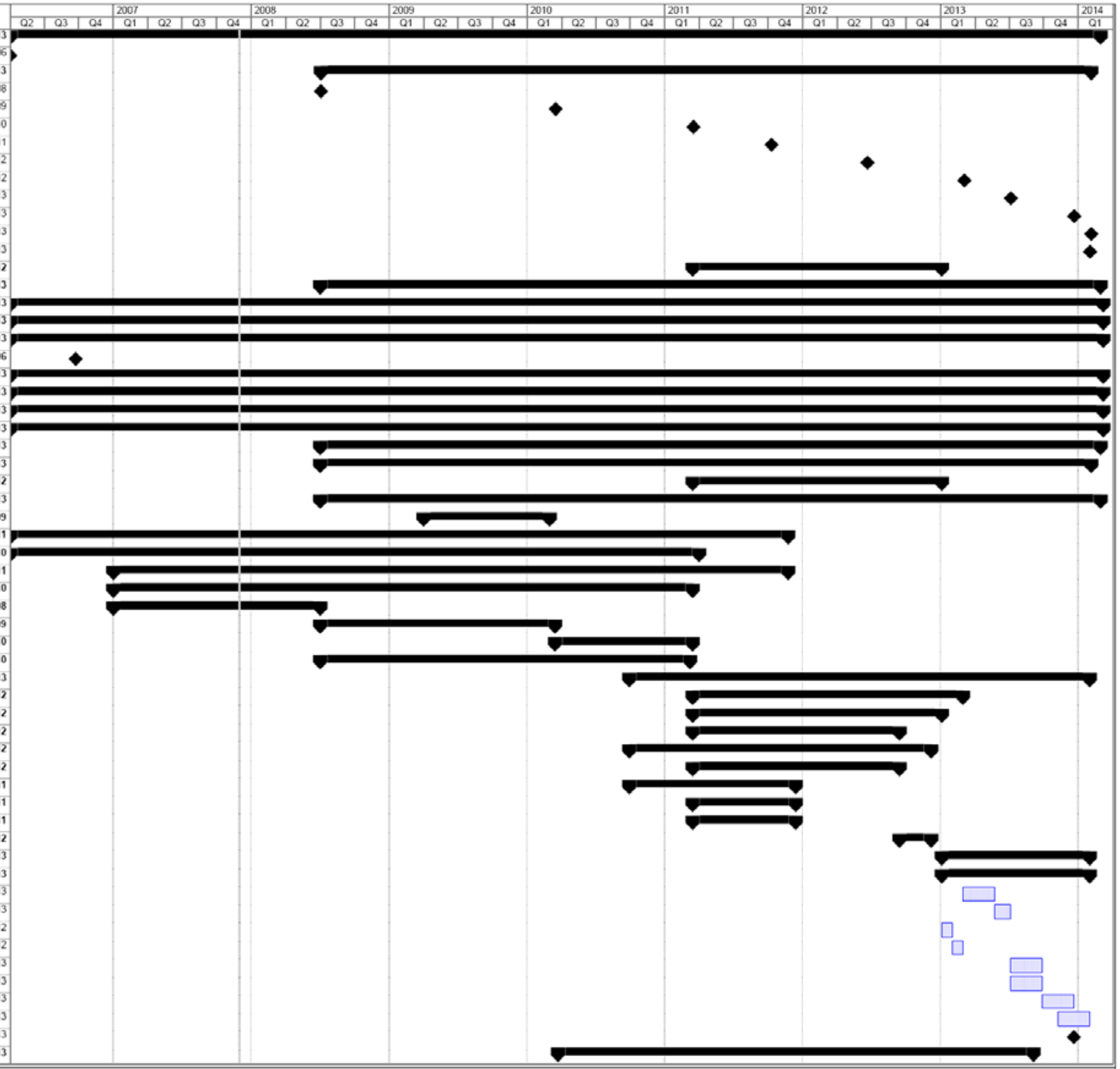

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Figure 22: Full NGAO project schedule