Keck Adaptive Optics Note 582

Keck Next Generation Adaptive Optics Guide Star Laser Systems

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1 INTRODUCTION

The essential characteristics of a laser system[1] used to generate an artificial adaptive optics (AO) "guide star" by spontaneous emission from sodium atoms in the mesosphere are how many photons are returned to the telescope aperture, and how well that flux is concentrated. Both of these characteristics determine the signal to noise ratio that can be realized by the wavefront sensor, which in turn affects the accuracy of the wavefront phase measurements, and therefore the quality of the wavefront correction delivered by the AO system.

The W. M. Keck Observatory (WMKO) Next Generation AO (NGAO) system design is based on using laser systems with performance at least equal to the best available from the current generation of deployed guide star laser systems. There are two such systems in operation that represent technical lines of evolution that may be able to satisfy the NGAO photon return requirements. Since laser system cost and complexity scale with power, the laser system that generates photons most efficiently in terms of power is the most desirable choice.

Lasers systems suitable for NGAO are represented by the system currently deployed at the Starfire Optical Range (Denman et al. 2006) and the laser systems currently under development for the Gemini South Observatory and the Keck I telescope (Hankla at al. 2006). Neither of these systems is readily available for acquisition by the NGAO project, but the lasers eventually purchased for NGAO will most likely use similar design approaches and technology.

In the following sections the technical approaches and key risk areas for candidate laser systems will be described, followed by a discussion of the laser system requirements. The final sections will discuss the basis for the laser system cost estimates for NGAO, and the issues of development and procurement.

[1] While the term "fasor" has been suggested as a more appropriate acronym for the coherent radiation sources described here, it is also associated primarily with the Starfire single frequency design. To avoid perception of bias we avoid this term and use the term "laser system" instead.

2 GUIDE STAR LASER SYSTEM TECHNOLOGIES

Building a laser system with the ~589 nm output power required to produce useful spontaneous emission by mesospheric sodium atoms is a challenge. There are no solid state materials that produce laser light at this wavelength and except for dye lasers, no known compounded materials that will produce the desired wavelengths. This leads to laser systems that employ some form of non-linear effect to multiply or heterodyne longer wavelength laser sources to produce the desired wavelength.

The rarified nature of the sodium concentration in the mesosphere makes it difficult, if not impossible, to develop laboratory experiments to establish the optimum way to maximize the photon return. A study of the atomic absorption spectrum of sodium has revealed the structure of the strongest atomic absorption feature, the D line. Based on quantum electrodynamics, the hyperfine structure of the D line is well understood and forms the basis for current theories about the interaction between a laser light source and spontaneous emission by the sodium atoms in the mesosphere (Milonni et al. 1998, 1999).

While it is important to keep in mind that the actual optical power required at 589 nm is a function of how efficiently photons are generated, and it is known that this efficiency is directly affected by the nature of the laser system output (spectral bandwidth, type of emission, and polarization), the estimates for NGAO have converged around the need for a total power of 150 watts for the purpose of generating multiple laser guide stars to support tomographic reconstruction of the atmospheric turbulence. In this discussion we will focus on laser systems that have demonstrated power levels of at least 50 watts since this power level appears to be commensurate with our requirements.

The general plan of current laser systems for guide star applications is the same, but each design differs in a number of key details that are helpful to understand when considering the development issues and risk areas for each approach.

A generalized block diagram of the laser systems under consideration for NGAO is shown in Figure 1.

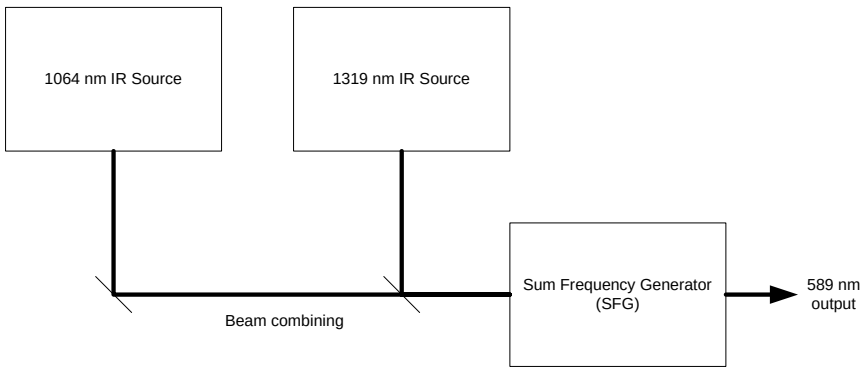

Figure 1: Generalized 589 nm laser system block diagram

The laser system consists of two infrared laser sources, one operating at a wavelength of 1064 nm and the second at a wavelength of 1319 nm. The light from these two lasers is overlapped spatially and temporally in a non-linear optical crystal (such as lithium triborate or LBO) to produce a sum frequency mixing product at 589 nm.

The power required for the IR laser sources is determined primarily by the efficiency of the sum frequency generation (SFG) process. While non-linear materials have been experimentally demonstrated that can produce higher conversion efficiencies, the most proven material remains LBO. Single pass conversion in LBO has efficiencies of ~35%, while resonant enhancement designs (Moore 2002, Denman et al. 2005) can have efficiencies of ~65%. Table 1 lists the IR power levels required to obtain 50 watts at 589 nm for these two conversion schemes.

Since the SFG process requires one photon at each input wavelength to produce one photon at the sum frequency, an optimum condition for operation of the SFG is obtained by adjusting the power levels of the two inputs to yield a photon balanced condition, that is, the power of the 1064 nm source is set to 1.24 times the power of the 1319 nm source.

SFG Configuration	**Estimated Conversion Efficiency**	**Total IR power**	**1064 nm power**	**1319 nm power**
Single pass	35%	143	79	64
Resonant enhancement	65%	77	43	34

Table 1: IR laser powers for various SFG efficiencies to give 50 watts SFG output

An important characteristic of a laser system for guide star applications is a stable output power and frequency. Stable power is particularly important for wavefront sensing configurations that require subtraction of the Raleigh scattered flux to improve the quality of the wavefront sensing. In the SFG process the output frequency and power stability are determined by the stability of the inputs, and for the wavelengths of interest for the infrared sources there are two alternatives for high stability and stable frequency operation: mode locked lasers or single frequency lasers.

At the infrared wavelengths of 1064 nm and 1319 nm, it is relatively easy to build a solid state laser using optically pumped Nd:YAG as the gain medium in conjunction with an external cavity. In CW operation the output of such a laser consists of a number of frequencies each corresponding to one of the axial modes in the cavity. Each mode has random phase with respect to any other mode, and while the power output of this laser appears continuous, over time the phase relationships of the modes will vary, resulting in interference between them and a corresponding fluctuation in the laser output. By using active mode locking, a technique to modulate the gain of the laser cavity in synchronization with the round trip time, the laser output becomes a well-defined pulse with a repetition rate equal to the round trip time and with stable amplitude. For a given laser configuration the output spectral bandwidth of the mode locked laser is determined by the width of the pulse. Maximizing power output and stability tends to favor narrower pulse widths, resulting in a correspondingly wider bandwidth.

Mode locked oscillators are capable of relatively high power outputs, from tens to hundreds of watts, but they typically have output spectral bandwidths of 500 to 1500 MHz.

Single frequency operation requires that only a single laser mode be allowed to propagate in the laser cavity. One commonly used design for single frequency lasers is the non-planar ring oscillator or NPRO (Kane et al. 1985). These are easily tuned and reliable devices, but only produce low output powers, typically less than 1 watt. The have very narrow output line widths of 10 KHz or less.

While a mode locked oscillator could be used directly to drive the SFG process, as the power levels increase the beam quality of the laser tends to decrease. The efficiency of the SFG process is directly affected by the beam quality and matching of the input beams, and as a result current implementations use mode locked oscillators in conjunction with optical power amplifiers to reach the required power levels for the SFG output.

The optical power amplifier is pumped with light from high power laser diodes. The energy supplied to the gain medium is released by stimulated emission at the wavelength of the input laser beam. Efficient operation of optical power amplifiers requires that the input beam extract most of the pump power in order to prevent spontaneous emission in the amplifier, this becomes a particular problem when operating at 1319 nm. This leads to a relatively high input power requirement for the first stage of laser amplification, typically 10 to 15 watts minimum. In properly designed amplifiers the output beam quality is determined primarily by the input beam quality, and with careful attention to detail reasonable performance can be obtained.

As a result, since a mode locked power oscillator offers relatively high output power, it is well suited to optical power amplification, and the resulting systems using several stages of optical amplification can easily reach the power levels required in Table 1 for single pass SFG operation.

In the laser systems currently being developed for the Gemini South Observatory and the Keck I telescope, mode locked oscillators followed by power amplifiers provide the IR sources, and single pass SFG is used to generate the 589 nm output. The single pass SFG configuration is relatively tolerant with respect to input beam quality, with the SFG process acting as a “spatial mode cleaner” due to the fact that the non-overlapping portions of the input beams are not converted.

As noted earlier, lasers that offer single frequency operation such as the NPRO have lower power outputs, making them ill-suited as the input to an optical power amplifier. An alternative approach is to injection lock a high power oscillator using a single frequency laser such as an NPRO. By injection locking a slave laser, such as a ring laser, the slave laser is forced to operate on a single mode at the same frequency as the injection laser. This approach is used in the laser system developed for the Starfire Optical Range 3.5 m telescope. In the Starfire laser system design two injection locked lasers are used in conjunction with a resonant enhancement SFG. A fundamental requirement of such a

design is precise mode matching between the two input beams and the resonant SFG cavity. This leads to a requirement for essentially diffraction limited performance for both injection locked oscillators and results in very high output beam quality from the SFG.

As can be appreciated from Table 1 the two approaches differ significantly in terms of IR power requirements, and therefore in terms of operating efficiency. In addition the two approaches are likely to differ in output beam quality, and are clearly differentiated by their output spectral bandwidths.

3 RETURN EFFICIENCY

The literature contains a number of discussions of the photon return efficiency of various laser systems, as well as estimates of the density of the mesospheric sodium layer and comparisons to the theory of sodium layer excitation as presented by Milonni et al. (1998 and 1999). The largest uncertainty in the current understanding is the degree to which optical pumping occurs with a narrow bandwidth source and circular polarization. These issues are more fully considered in another document by this author. For the purposes of this document we will confine the discussion to reported photon return efficiencies, which we will employ without comment.

In July 2005 a simultaneous projection test of the Gemini North and Keck II laser systems was conducted. Each Observatory made observations of both projected spots. The results are summarized in KAON-419 (Neyman, 2005). Based on these results we find a return efficiency for the Gemini North laser system of 22 photons/s/cm^2/W. This is a mode locked laser system with an output spectral bandwidth of ~1 GHz.

For the single frequency laser system we reference the results of tests at Starfire Optical Range in the latter half of 2005 (Denman et al. 2006). It appears that all of the results reported in this paper are for powers measured prior to the laser beam transport and launch optics, so for comparison with the Gemini North results, and with the methodology employed in the NGAO simulations to compute launched laser power we have corrected the reported power values by assuming launch path transmission of 82%.

Using results reported for circular polarization in this time period and correcting for the presumed launch path transmission, we obtain a range of photon return efficiencies from 90 to 229 photons/s/cm^2/W. The mean of four reported values is 146 photons/s/cm^2/W, while the mean of the range of values given in the conclusions (pp. 62721L-12) is 162 photons/s/cm^2/W after correction for launch path transmission. As a result we have adopted an “average” photon return of 150 photons/s/cm^2/W for a single frequency laser system with circular polarization.

However, it should also be noted that in this same paper (Denman et al. 2006) a yearly average is reported of 110 photons/s/cm^2/W, which after correction for launch path transmission yields 134 photons/s/cm^2/W.

Simultaneous independent measurements for sodium column density during the measurements reported above were not available. However, in KAON-419 the estimated for sodium column density at the time of the Gemini North return measurements is 1.8 x 10^9 atoms/cm^2. These values are considerably lower than reported in Roberts et al. (2007) where an average column density of 4.3 x 10^9 atoms/cm^2 is reported.

4 BASELINE LASER SYSTEM REQUIREMENTS FOR NGAO

During the preliminary design phase of the AO system for NGAO a complete requirements document will be developed for the laser systems. In this section we summarize the most significant performance and implementation requirements for the laser systems as "baseline" or starting point requirements for the laser systems. These requirements are based on flow down from the NGAO system requirements, informed by experience gained in the development of the laser systems for the Gemini South Observatory and the Keck I telescope.

A number of additional, more detailed requirements are essential to describe a laser system that is fully compliant with all applicable safety regulations and compatible with WMKO operations, the majority of these are covered in the Observatory's standard requirements for Nasmyth platform instruments with the exception of specific laser safety requirements.

4.1 Optical Requirements

The NGAO system design proposes a reconfigurable guide star asterism with a variable number of guide stars. The error budget assumes a certain number of photons will be available at the top of the atmosphere, and then divides this assumed number of photons up among the appropriate number of guide star images (based on the selected asterism) when computing the wavefront sensing signal to noise ratio.

The NGAO system design error budget assumptions are as follows:

1. Total guidestar photon return at the top of the atmosphere: 14868 photons/s/cm^2
2. Photon return efficiency: 150 photons/s/cm^2/W
3. Uplink transmission losses for an observation at a 30º zenith angle: 34%

This leads to a requirement of 150 watts total laser power, and for the purposes of this discussion we assume that this will be provided by three 50 watt lasers for the reasons given in §2. It should be noted that for cost reasons the NGAO system design also considers a possible phased deployment of lasers, starting with a 100 watt total power requirement delivered by two 50 watt lasers, and then adding a third 50 watt laser at a later time.

The baseline optical performance requirements for the NGAO laser systems are summarized in Table 2. These requirements are the result of a flow down from key NGAO system requirements as follows:

1. 150 watts total laser power, 50 watts per laser
2. Beam transport via either free space or single mode optical fiber
3. Tunable off the sodium lines for Rayleigh calibration
4. Emission compatible with the NGAO passbands

The optical requirements for the NGAO laser systems are driven by the assumption of a return efficiency of 150 photons/s/cm^2/W. As discussed in the section on return efficiency, to date this performance has only been achieved by a single frequency laser system with 10 MHz line width and a circularly polarized beam derived from a linearly polarized output with a high degree of polarization purity. The photon return assumption also implies precise tuning to the peak of the sodium D_{2a} line. While this also appears to down select to the Starfire laser system design, it is conceivable that a single frequency design could evolve from the technologies used in the laser systems under development for the Gemini South Observatory and the Keck I telescopes.

The requirements grouped under beam characteristics in Table 2 describe a beam suitable for efficient beam transport via either a fiber optic or free space beam transport system, and for subsequent launch and imaging on the sodium layer as a uniform spot with a size limited by the launch telescope aperture and the seeing conditions and not by the beam quality of the laser system. The polarization requirement is derived directly from the expected operation with a retarder to achieve a circularly polarized beam. Consideration of the potential impact of a fiber optic beam transport on effective power output and polarization purity is beyond the scope of this discussion, but it should be recognized that fiber optic beam transport is problematic due to both the power level involved and the possible impact on polarization purity and stability.

The requirements grouped under spectral characteristics in Table 2 describe a laser system output with the central wavelength and spectral bandwidth required to achieve the desired photon return efficiency of 150 photons/s/cm^2/W. Additional requirements specify frequency stability consistent with the specified power stability, and tunability in support of calibration of the LGS wavefront sensor background due to Rayleigh scattering of the outgoing laser beam. The out of band power requirement limits unwanted output from the laser system to aid in controlling stray light in the NGAO passbands that could affect the sensitivity of science observations.

4.2 Mechanical Requirements

The baseline mechanical performance requirements for the NGAO laser systems are summarized in Table 3.

The requirements for the operating environment flow down from the ambient and seismic conditions at the summit of Mauna Kea. The vibration requirements also address

compatibility with the vibration sensitive environment of the Keck telescope and instrumentation.

The requirements for mass, size and power dissipation reflect reasonable assumptions regarding the size and location of the laser system enclosure. These requirements also anticipate a self-contained single unit for each laser system with a minimal number of external interconnections. In addition to the requirements of Table 3, the fact that the NGAO laser facility will require three 50 watt laser systems implies a need for special attention to service and maintenance issues. In particular the laser systems should provide modular construction to permit rapid replacement of components during servicing and to facilitate access for alignment and maintenance.

4.3 Electrical/Electronic Requirements

The baseline electrical/electronic performance requirements for the NGAO laser systems are summarized in Table 4. The power input requirements flow down from the Observatory facilities, and the start-up and shutdown time requirements flow down from operational needs including a reasonable restart time after a power failure.

The laser systems will be expected to incorporate built-in test features as required to monitor operation and optimize performance to achieve the optical performance requirements and various operational requirements.

4.4 Interfaces

The laser system shall provide interfaces for power input, cooling, laser output, emergency power off, dedicated operators and engineering displays, and Keck keyword library compatible control of all functions. All control functions with the exception of emergency power off shall be accomplished through a TCP/IP compatible network interface of a format and data rate appropriate to the performance requirements for the dedicated displays and keyword interface.

4.5 Software

The laser system shall provide all software required for start-up, operation (including data logging for all internal sensors and diagnostics), routine calibration and alignment, routine maintenance, and shutdown, including emergency shutdown. Efficient operation requires that the laser system automatically perform all functions required for normal operation. The laser system shall support a dedicated operator's display, a dedicated engineering display, and a Keck keyword library compatible interface for all software controlled functions.

4.6 Safety

The laser system shall comply with IEC 60825-1, "Edition 1.2: Safety of Laser Products – Part 1: Equipment classification, requirements, and user's guide". The suitability of this compliance is based on CDRH publication "CDRH Laser Notice #50: Laser Products – Conformance with IEC 60825-1, Am. 2 and IEC 60601-2-22; Final Guidance for Industry and FDA".

4.7 Maintenance and Service

The NGAO system level requirements for up time are flowed down to requirements for maintenance and service. The time required for routine maintenance or replacement of consumable components shall be minimized. No such procedure involving an individual component shall take more than 30 minutes to perform. The mean time to repair the laser system for all but catastrophic failures (those failures that result in damage to multiple related components) shall not exceed 1 hour provided that spare parts are on hand.

Table 2: Baseline optical performance requirements

Parameter	*Min.*	*Typ.*	*Max.*	*Units*	*Notes*
Power characteristics					
Output power	50	-	-	W	1
Stability	-	1	5	%	2
Beam characteristics					
Diameter	2	-	5	mm	3,4
Quality					
Spatial mode	-	TEM_{00}	-	N/A	
M^2	1.0	-	1.2		3
Ellipticity	1.0		0.95	N/A	3,5
Stability	-	-	5	%	6
Pointing stability					
Transverse	-	-	10	%	3,7
Angular	-	-	40	μrad	3,8
Polarization	200	-	-	:1	3,9
Spectral characteristics					
Nominal central wavelength	-	589.1591	-	nm	10
Central wavelength stability	-	-	0.15	%	11
Tunability					
Frequency range	±3.1	-	-	GHz	12
Tuning rate	100	-	-	MHz/s	13
Tuning resolution	50	-	-	MHz	
Spectral bandwidth	-	-	10	MHz	14
Out of band power	-	-	0.1	W	3

Notes:

1. Absolute minimum power in watts at the nominal central wavelength within a circular aperture enclosing 99% of the encircled energy of the laser beam.
2. Peak to peak fluctuation in the output power at the laser system output aperture over a 12 hour period 30 minutes after start-up from a complete shutdown of at least 8 hours.
3. In the plane of the laser system output aperture.
4. Measured at the $1/e^2$ intensity points.
5. Ellipticity is defined here as the amount by which the radial distance from the center of the beam to any point with a given average intensity can vary with respect to the radial distance from the center of the beam to any other point with the same average intensity. A perfectly circular two-dimensional beam profile would have an ellipticity of 1.
6. Percentage variation in the M^2 value over a 12 hour period 30 minutes after start-up from a complete shutdown of at least 8 hours.
7. Peak to peak transverse motion of the output beam as a percentage of the beam diameter.
8. Peak to peak variation in the angular tilt of the output beam over a 12 hour period 30 minutes after start-up from a complete shutdown of at least 8 hours.
9. Linear polarization purity of the laser output.
10. The nominal central wavelength should correspond to the peak of the sodium D_{2a} line.
11. Percentage variation in the central wavelength over a 12 hour period 30 minutes after start-up from a complete shutdown of at least 8 hours.
12. With respect to the nominal central wavelength, assumes symmetrical tuning about the sodium D_{2a} line.
13. Increasing or decreasing frequency within the tuning range. Monotonic response free of hysteresis.
14. At the FWHM of the spectral bandwidth curve.

Table 3: Baseline mechanical performance requirements

Parameter	*Min.*	*Typ.*	*Max.*	*Units*	*Notes*
Operating environment					
Altitude	0	-	4300	m	
Temperature					
Ambient	-10	0	20	ºC	1
Rate of change	-	-	±1	ºC/h	
Humidity	0	-	90	%	2
Gravity Orientation	-	-1	-	g	3
Vibration	-	-	$1x10^{-5}$	g^2/Hz	4,5
Seismic					
Shock	-	-	15	g	6,8
Acceleration	-	-	2	g	7,
Dust and particulates	-	-	-	-	9
Mass	-	-	1000	kg	
Overall dimensions					
Linear	-	-	1.2	m	10
Volume	-	-	1.5	m^3	
Power dissipation					
To ambient	-	-	100	W	
To coolant supply	-	-	10,000	W	

Notes:

1. The temperature of the enclosure where the laser system is located shall change by no more than 2 ºC in a 12 hour period.
2. Relative, non-condensing.
3. Normal to the earth's surface.
4. 20 to 1000 Hz, 6 db/octave drop-off to 2000 Hz.
5. The laser system shall be compatible with a generic vibration criteria curve "C" environment.
6. 0.015 s half-sine, all axes.
7. 0.5 Hz to 100 Hz all axes.
8. The laser system shall conform to the zone 4 earthquake survival requirements of Telcordia Standard GR-63-CORE, "NEBS Requirements".
9. The enclosure where the laser system is located shall conform to the class 10,000 requirements of Federal Standard 209E.
10. Maximum linear dimension of any side of a cubic volume that completely encloses the volume occupied by the laser system.

Table 4: Baseline Electrical/Electronic performance requirements

Parameter	*Min.*	*Typ.*	*Max.*	*Units*	*Notes*
Power input					
Voltage	187	208	229	Vac	1
Current	-	-	40	Amperes	
Frequency	57	60	63	Hz	
Power factor	0.9	-	-	-	
Start-up time	-	-	30	min	2
Shutdown time	-	-	30	min	3

Notes:

1. 3 phase, 4 wire and ground supply.
2. Immediately after a normal shutdown, and no more than 30 minutes after an emergency shutdown.
3. Normal shutdown.

5 DESIGN AND DEVELOPMENT ISSUES

As discussed earlier in this document, there are two demonstrated designs that have the potential to meet the NGAO requirements. One is a mode locked laser system that has some advantage in being the second prototype development based to a limited extent on a deployed system. The other is a single frequency design that is represented by only one prototype system, albeit one that is in regular operation at the Starfire Optical Range.

The mode locked laser systems being developed for the Gemini South Observatory and the Keck I telescope are related to the system developed for Gemini North, as both of the new systems employ similar power oscillator designs and also use some of the electronic subsystem designs and software components developed for Gemini North. The design of the two new laser systems are based on many common components with the principle difference being the number of power amplifiers employed for the IR sources since the Keck I laser system is only required to produce 20 watts output at 589 nm. Both laser systems are quite large (2320 x 3660 x 1150 mm) and heavy (> 2500 kg), and in addition to the laser system bench enclosure the electronics and coolant control systems are enclosed in a two bay, six foot tall equipment rack. The laser systems are constructed using laboratory optical bench techniques and should still be considered prototypes, not production systems. The laser systems are being constructed to meet many of the Observatory's standard requirements, including the operating environment and seismic conditions.

A particular limitation of the mode locked design is the wide output spectral bandwidth. This design offers a lower return efficiency than the alternative, single frequency design. In order to obtain the baseline photon return a total of 350 watts of mode locked optical power at 589 nm would be required, and it is likely that saturation effects would limit the return flux to a level significantly below the required value.

The single frequency design satisfies the baseline photon return with a total of 50 watts of optical power at 589 nm. The existing laser system would serve as the basis for development of a second generation system, and more nearly represents the desired envelope requirements and configuration, although in its present form it is also accompanied by two electronics racks, with approximately the same total panel area as the mode locked laser system design. The existing prototype does not meet many of the Observatory's standard requirements, and has not been designed for the corresponding operating environment and seismic conditions.

In order for either laser system design to be suitable for use by NGAO a significant additional development effort will be required. In the case of the mode locked design it will be necessary to modularize the laser system design in order to make multiple laser systems more practical to support, and to scale up the output power to meet the baseline photon return requirement within a reasonable envelope size. It may also be possible to employ the core technologies of this design to realize a single frequency laser system, but that is speculative notion at this point. The development effort for this laser system will involve a significant amount of electro-optical development work as well as more routine

production engineering work. The software will also require further development effort to support the Keck keyword library.

In the case of the existing single frequency design, the required development is primarily production engineering work. While a limited amount of electro-optical development may be required to address issues of modularity and maintainability, as well as potential issues with availability of components, these are lower risk activities with well defined objectives and timelines. Software development will also be required to support the Keck keyword library.

The most significant issues for acquisition of laser systems for NGAO are the lack of production laser systems and the high cost of the laser systems. The high cost is in part because of the lack of a sufficiently developed market that can support the two key elements of cost reduction, production engineering and volume purchases of components and subassemblies. Commercial suppliers are unlikely to spend the money needed to meet NGAO requirements unless a stronger business case can be developed. To address this issue it is recommended that WMKO and the Thirty Meter Telescope (TMT) project work together to develop a common set of laser system requirements, resulting in an opportunity for a supplier to build at least six identical 50 watt laser systems. While this is still a limited business case it does begin to approach a scale that may be attractive to a commercial supplier under the right conditions.

It should also be noted that since both projects will actually use these laser systems as sources for multiple guide star asterisms with as many as nine guide stars, a larger number of smaller laser systems could also satisfy the power requirements. The trade off between quantity and cost should be explored, since it also offers a more graceful degradation of laser facility performance in the event of a laser system failure.

This document will not provide any details of anticipated laser system costs, as this is a subject that is considered highly confidential at this stage. There are concerns regarding cost for both WMKO and potential suppliers, and future negotiations for supply of laser systems can easily be damaged by early disclosure of cost estimates. In addition WMKO has access through the current development programs to information that should be protected for reasons of discretion and confidentiality. What can be said at this point is that the current estimates are all a significant portion of the NGAO cost to completion. The high laser system costs are viewed by the NGAO project as a significant challenge.

While the single frequency design is clearly optimal from a photon return efficiency viewpoint, it is not clear how this laser system design can be made available for purchase by NGAO and the TMT project. The Air Force Research Laboratory is accustomed to collaborating with commercial suppliers to get technology for the Air Force, but a mechanism for technology transfer in the other direction is not well developed. An attempt was made to form a business arrangement to build laser systems for Gemini and WMKO, but this was abandoned due to perception by Gemini that the programmatic risks were too high relative to the offer from the supplier of the Gemini North laser system for laser systems based on the Gemini North design with a promise of delivery

consistent with Gemini's schedule at the time which required the laser system for Gemini South in summer of 2006.

The outcome of that decision is still unresolved, but it is anticipated that laser systems that meet the current WMKO and Gemini performance requirements (but not the NGAO requirements) will be delivered within calendar 2008, approximately 2 years later than originally proposed by the supplier.

As discussed above the mode locked design will require significant electro-optical development work to scale to the power levels required to meet the NGAO photon return requirements. There is significant risk associated with this approximately 3 fold power scaling, and in addition it is anticipated that the higher power levels may not achieve the required photon return due to saturation effects in the sodium layer.

Both laser system designs rely on a number of specialized optical materials and components with limited sources of supply and long lead times. This results primarily in cost and schedule risk, not technical risk. In both designs the high power IR sources rely on high power laser diodes to provide pump light. These diodes are produced commercially for a variety of DPSS laser applications, but the highest power devices are made in small quantities, and being relatively new components they have a limited operating history and are subject to design changes, some of which may force a redesign of the power amplifiers or slave lasers in the two potential NGAO laser system designs, a significant technical risk.

As also discussed above, both laser system designs will require significant production engineering to make them field ready for deployment in the numbers required for NGAO and the TMT. The scope of technical risk is limited, but the process will require a reasonably long time line with careful design analysis and perhaps some prototyping to achieve a result with good reliability and maintainability.

To conclude, the principle risks for the NGAO laser systems may be summarized as follows:

1. No production laser system available
2. Limited business case for a commercial supplier
3. No clear path to production of the single frequency design
4. Development work is required for the power levels needed to use a mode locked design, additional risk that higher power may not achieve the required photon return levels due to saturation
5. Key components such as high power pump diodes remain difficult to obtain and of uncertain lifetime
6. Significant production engineering required to field systems ready for NGAO scale deployment
7. Laser system costs are high

6 BASELINE LASER SYSTEM ACQUISITION PLAN

As part of the planning for the remaining phases of the NGAO project a plan has been developed for the acquisition of the NGAO laser systems. This plan is based on the experience gained in the development of the laser systems for the Gemini South Observatory and the Keck I telescope and other extensive experience in the development of instrumentation for WMKO.

The strategy of the laser system acquisition plan is to develop a set of common requirements that maximizes the number of identical laser systems to be built and then to offer the opportunity to build these laser systems to appropriate commercial suppliers that may be either an existing company or a start up venture.

The first step will be to first work with the AO design team in the NGAO project, and with the corresponding team of the TMT project to develop a complete set of requirements for laser systems suitable for both projects. These requirements will also be discussed with potential suppliers to obtain technical input and assessments of feasibility. Once the requirements are completed a request for proposals (RFP) will be issued. Based on the responses to this RFP a contract will then be negotiated for the development activities for the laser systems. With satisfactory completion of this contract a second contract will then be issued for the supply of the laser systems. Both of these phases are expected to include participation by both WMKO and the TMT in order to make the business opportunity as attractive as possible for the potential suppliers.

If an arrangement cannot be made for commercial supply, or if the collaboration with the TMT is not possible, a fall back strategy will have to be developed. This is could be a development activity at one of the collaborating partners of WMKO, or some other arrangement to obtain the required development and production resources.

The laser system acquisition plan consists of four phases, preliminary design, detailed design, full scale development, and delivery and commissioning. The timing of each phase has been established based on the end goal of delivering laser systems near the mid-point of the NGAO delivery and commissioning process.

The preliminary design phase will deliver four documents, a laser system requirements document, a preliminary laser system interface control document (ICD), a laser system RFP, and a report on the RFP response.

The laser system requirements development process will begin with a detailed analysis of the anticipated laser system performance and the corresponding performance impacts on the AO system. This will be followed by analysis of the laser system requirements, and then the development and documentation of the laser system requirements. Once the laser system requirements document is complete a preliminary laser system ICD will be developed, also in collaboration with the AO design team. After review by the NGAO project these documents will form the technical basis for the RFP.

The laser system RFP process will start with the drafting and review of the RFP document. The RFP will then be released to potential suppliers. After a suitable response period the responses will be reviewed and a report written on the responses. The laser system preliminary design phase will conclude with the issuing of a contract for the laser system development activities, initiating the laser system detailed design phase.

The primary deliverables from the detailed design phase consist of detailed designs for each of the elements of the laser system product structure shown in Figure 2. This product structure is based on a generic laser system architecture compatible with both mode locked and single frequency designs. The detailed design phase will also deliver final specifications for the laser systems, a final ICD, an acceptance test plan, and a detailed design report including the schedule and budget for supply of the laser systems.

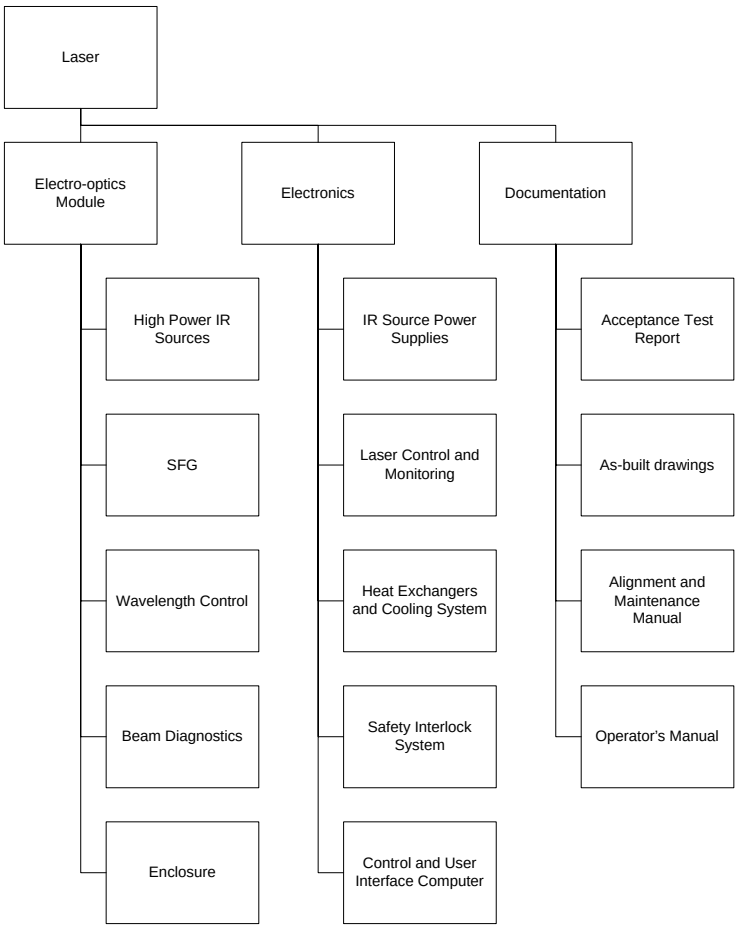

Figure 2: Laser system product structure

Based on the successful completion of the detailed design phase a full scale development phase will commence with the issuing of a contact for supply of the laser systems. During this phase a first production prototype laser system will be built and tested followed by production of additional laser systems as required by the contract. If a negotiation for supply to both WMKO and TMT is successful the production period is expected to last approximately 3 years.

The full scale development phase finishes with a factory acceptance test of each laser system. The laser systems are then delivered to the WMKO base facility for final acceptance testing. After installation at the summit the supplier will provide operations and maintenance training to WMKO staff.

The major milestones for NGAO laser system development and the overall NGAO project are summarized in Table 5. The laser system milestones are shown in boldface type.

Table 5: Laser system milestones

Milestone	Date
NGAO PD Start	May 5, 2008
Laser Contract Issued	June 15, 2009
Laser DD Start	July 13, 2009
NGAO PDR	September 21, 2009
NGAO DD Start	November 3, 2009
Laser DDR	December 14, 2010
NGAO DDR	May 17, 2011
NGAO FSD Start	June 29, 2011
Laser Production Prototype ATP Complete	April 12, 2012
NGAO DC Start	May 1, 2013
Laser PSR	November 4, 2013
Laser Delivery	December 4, 2013
Laser Production Complete	December 5, 2013

An overview of the schedule for NGAO laser system development is shown in Figure 3.

ID	WBS	Task Name	Start	Finish	Work
1	5.2	Laser	Mon 5/5/08	Thu 1/9/14	42,482 hrs
2	5.2.1	Laser Milestones	Mon 5/5/08	Fri 12/6/13	0 hrs
16	5.2.2	Laser Project Management	Mon 5/5/08	Thu 1/9/14	5,344 hrs
17	5.2.2.1	Laser Project Meetings	Thu 7/9/09	Thu 1/9/14	3,520 hrs
73	5.2.2.2	Laser Budget and Schedule Maintenance	Mon 5/5/08	Thu 1/9/14	480 hrs
74	5.2.2.3	Laser Documentation	Mon 5/5/08	Thu 1/9/14	480 hrs
75	5.2.2.4	Laser Reporting	Mon 5/5/08	Thu 1/9/14	480 hrs
76	5.2.2.5	Laser Reviews	Tue 12/14/10	Wed 11/20/13	384 hrs
77	5.2.2.5.1	Laser DDR	Tue 12/14/10	Wed 12/15/10	128 hrs
78	5.2.2.5.2	Laser ATP Review	Thu 4/12/12	Fri 4/13/12	128 hrs
79	5.2.2.5.3	Laser PSR	Mon 11/18/13	Wed 11/20/13	128 hrs
80	5.2.3	Laser Preliminary Design	Mon 5/5/08	Fri 5/29/09	520 hrs
81	5.2.3.1	Laser Requirements	Mon 5/5/08	Fri 10/3/08	160 hrs
82	5.2.3.1.1	Laser Performance Analysis	Mon 5/5/08	Fri 5/30/08	40 hrs
83	5.2.3.1.2	Laser Requirements Analysis	Mon 6/2/08	Fri 6/27/08	40 hrs
84	5.2.3.1.3	Laser Requirements Development	Mon 6/30/08	Fri 7/25/08	40 hrs
85	5.2.3.1.4	Laser Requirements Drafting and Revisions	Mon 7/28/08	Fri 10/3/08	40 hrs
86	5.2.3.2	Laser Preliminary ICD	Mon 7/28/08	Fri 8/22/08	40 hrs
87	5.2.3.2.1	Laser ICD Drafting and Revisions	Mon 7/28/08	Fri 8/22/08	40 hrs
88	5.2.3.3	Laser Request for Proposals (RFP)	Mon 10/6/08	Fri 2/6/09	120 hrs
89	5.2.3.3.1	Laser Proposal Drafting	Mon 10/6/08	Fri 10/31/08	40 hrs
90	5.2.3.3.2	Laser Proposal Release	Mon 11/3/08	Fri 11/14/08	40 hrs
91	5.2.3.3.3	Laser Proposal Response Period	Mon 11/17/08	Fri 2/6/09	40 hrs
92	5.2.3.4	Laser RFP Response Report	Mon 2/9/09	Fri 4/3/09	120 hrs
93	5.2.3.4.1	Laser Proposal Evaluation	Mon 2/9/09	Fri 3/6/09	40 hrs
94	5.2.3.4.2	Laser Response Discussions	Mon 3/9/09	Fri 4/3/09	40 hrs
95	5.2.3.4.3	Laser Report Drafting and Revisions	Mon 3/9/09	Fri 4/3/09	40 hrs
96	5.2.3.5	Laser Contract	Mon 4/6/09	Fri 5/29/09	80 hrs
97	5.2.3.5.1	Laser Contract Drafting and Revisions	Mon 4/6/09	Fri 5/1/09	40 hrs
98	5.2.3.5.2	Laser Contract Negotiations	Mon 5/4/09	Fri 5/29/09	40 hrs
99	5.2.4	Laser Detailed Design	Tue 6/16/09	Mon 12/13/10	9,138 hrs
100	5.2.4.1	Laser Electro-optics Module	Tue 6/16/09	Mon 7/5/10	4,400 hrs
106	5.2.4.2	Laser Electronics Module	Tue 12/8/09	Mon 3/29/10	470 hrs
115	5.2.4.3	Laser Safety Systems	Tue 3/30/10	Mon 4/5/10	120 hrs
116	5.2.4.4	Laser Design Documentation	Tue 7/6/10	Mon 8/30/10	1,760 hrs
117	5.2.4.5	Laser Manufacturing Documentation	Tue 8/31/10	Mon 10/25/10	1,760 hrs
118	5.2.4.6	Laser Final Specifications	Tue 8/31/10	Mon 10/4/10	160 hrs
119	5.2.4.7	Laser Final ICD	Tue 10/5/10	Mon 10/25/10	68 hrs
120	5.2.4.8	Laser Acceptance Test Plan	Tue 10/26/10	Mon 11/29/10	160 hrs
121	5.2.4.9	Laser DD Report	Tue 11/30/10	Mon 12/13/10	240 hrs
122	5.2.5	Laser Full Scale Development	Thu 12/16/10	Thu 12/5/13	26,400 hrs
123	5.2.5.1	Laser Production Prototype	Thu 12/16/10	Wed 4/25/12	11,360 hrs
158	5.2.5.2	Laser Production Units	Thu 4/26/12	Thu 12/5/13	15,040 hrs
171	5.2.6	Laser Delivery and Commissioning	Thu 12/5/13	Thu 12/26/13	1,080 hrs
172	5.2.6.1	Laser On-site ATP	Thu 12/5/13	Thu 12/26/13	720 hrs
173	5.2.6.2	Laser Training	Thu 12/5/13	Thu 12/26/13	360 hrs

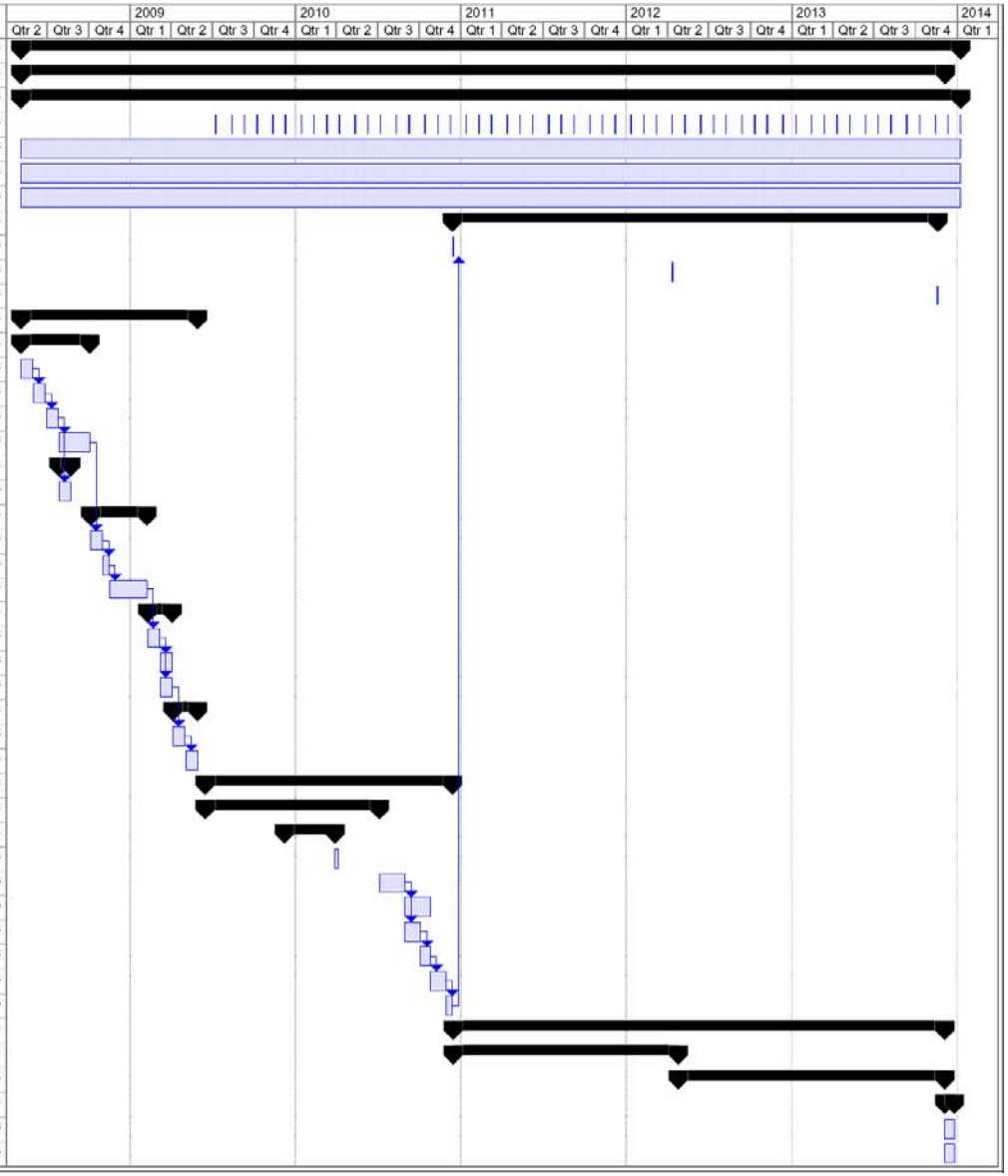

Figure 3: Laser system development schedule

7 REFERENCES

1. Denman, Craig A.; Drummond, Jack D.; Eickhoff, Mark L.; Fugate, Robert Q.; Hillman, Paul D.; Novotny, Steven J.; Telle, John M., "Characteristics of sodium guidestars created by the 50-watt FASOR and first closed-loop AO results at the Starfire Optical Range", Advances in Adaptive Optics II. Edited by Ellerbroek, Brent L.; Bonaccini Calia, Domenico. Proceedings of the SPIE, Volume 6272, pp. 62721L (2006).
2. Hankla, Allen K.; Bartholomew, Jarett; Groff, Ken; Lee, Ian; McKinnie, Iain T.; Moule, Grant; Rogers, Nathan; Tiemann, Bruce; Tracy, Allen J.; VanHoudt, Paul; Adkins, Sean M.; d'Orgeville, Céline, "20 W and 50 W solid-state sodium beacon guidestar laser systems for the Keck I and Gemini South Telescopes", Advances in Adaptive Optics II. Edited by Ellerbroek, Brent L.; Bonaccini Calia, Domenico. Proceedings of the SPIE, Volume 6272, pp. 62721G (2006).
3. P. W. Milonni, R. Q. Fugate, and J. M. Telle, "Analysis of measured photon returns from sodium beacons", J. Opt. Soc. Am. A 15, pp. 217-233 (1998).
4. P. W. Milonni, H. Fearn, J. M. Telle, and R. Q. Fugate, "Theory of continuous-wave excitation of the sodium beacon", J. Opt. Soc. Am. A 16, pp. 2555-2566 (1999).
5. Moore, G.T., "Resonant sum-frequency generation", IEEE Journal of Quantum Electronics, Volume 38, Issue 1, Jan 2002 pp. 12-18.
6. Denman, Craig A.; Hillman, Paul D.; Moore, Gerald T.; Telle, John M.; Preston, Joseph E.; Drummond, Jack D.; Fugate, Robert Q., "Realization of a 50-watt facility-class sodium guidestar pump laser", Solid State Lasers XIV: Technology and Devices. Edited by Hoffman, Hanna J.; Shori, Ramesh K. Proceedings of the SPIE, Volume 5707, pp. 46-49 (2005).
7. T. J. Kane and R. L. Byer, "Monolithic, unidirectional single-mode Nd:YAG ring laser", Opt. Lett. 10, 65- (1985).
8. Neyman, C., "Simple Models for the Prediction of Na Laser Guide Star Brightness and Comparison to Measured Returns from the Gemini and Keck Lasers", Keck Observatory Adaptive Optics Note (KAON) 419. July 14, 2005.
9. Roberts, Lewis C. Jr; Bradford, L.William; Neyman, Christopher R.; Liu, Alan Z., "Measurements of Mesospheric Sodium Abundance above the Hawaiian Islands", Publ. Astron. Soc. Pac., 119, 787-792 (2007) - 30.08.07 14.01.08 July 2007.