LGS AO photon return simulations and laser requirements for the Gemini LGS AO program

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ABSTRACT

Laser Guide Star Adaptive Optics system operation at an 8-m class telescope like Gemini North and Gemini South require minimum laser output power in the 10 W range. Since each additional Watt of laser power increases the laser purchase and operational costs, it is highly desirable to understand how laser parameters can be optimized in order to decrease the total laser power requirement. This paper provides some tools to calculate the output power requirement of a candidate laser system and its optimized parameters in the case of continuous wave lasers and high repetition rate pulsed lasers. Laser power requirements for Gemini North and Gemini South are given as examples of this calculation.

Keywords: Laser Guide Star Adaptive Optics, photon return, sodium/laser interaction efficiency, laser power requirements

1. INTRODUCTION

Gemini North and Gemini South, two IR-optimized 8-m telescopes respectively located at the summit of Mauna Kea, Hawaii, and Cerro Pachon, Chile, will soon be equipped with both Natural Guide Star (NGS) and Laser Guide Star Adaptive Optics (LGS AO) systems. The Gemini 8-m Telescopes Project LGS AO program includes three generations of laser systems to be implemented on one or the other sites. Providing funding is secured a 3 W continuous wave (CW) commercial dye laser will be the first laser system to come on line in mid-2001. Teamed with a curvature-LGS AO system [1], this laser system will enable LGS AO operation at Gemini South. The second, 10 W-class laser system will be associated with ALTAIR [2], the altitude conjugated- NGS AO system at Gemini North. The laser system will complete ALTAIR's upgrade to a LGS AO facility instrument in 2003. Last but not least, the third-generation, 5 x 10 W-class laser system will equip the proposed five-LGSs Multi-Conjugated Adaptive Optics (MCAO) system [3, 4, 5, 6, 7], the Gemini South facility AO module scheduled to come on line in 2004 pending definitive approval. All three LGS systems rely on the excitation of mesospheric sodium atoms to create the artificial wavefront reference required by Adaptive Optics systems where no NGS of sufficient brightness exist near the science target. Lasers emitting at the sodium D2 line wavelengh near 589 nm excite sodium atoms whose radiative decay creates the so-called laser guide star. In this technique, the efficiency of laser power to LGS brightness conversion depends substantially on the temporal, spectral and spatial format of the laser system used to excite sodium atoms. Thus laser systems with different characteristics (CW or pulsed, pulse length, repetition rate, spectral bandwidth, etc.) but the same average power do not produce LGSs of identical brightness. A complete theory of laser/sodium interaction includes as many parameters as the Doppler and hyperfine broadening of the sodium D2 line, the sodium column density, atmospheric parameters, transition saturation, optical pumping, radiation pressure, geomagnetic field effects, collisions, dwell time, diffusion and possibly other effects as well [8, 9, 10, 11, 12, 13, 14]. Most effects need to be accounted for when deriving the output power requirement of laser systems used for astronomical LGS AO applications. As a primer, section 2 describes the approach we have initially taken to estimate the output power requirements for the Gemini North 10 W and Gemini South 50 W-class laser systems. This approach did not take any saturation effects into account, so the power requirements needed to be revised depending on the temporal, spectral and spatial characteristics of candidate laser systems. Sections 3 and 4 present results obtained with models including saturation for two different laser formats, and estimate adequate power requirements for the Gemini North and Gemini South LGS systems.

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2. GEMINI LASER OUTPUT POWER REQUIREMENTS IN THE NO SATURATION LIMIT

2.1. Gemini North (Mauna Kea)

We simulated the ALTAIR response to a LGS source and used the results of the simulation to derive the photon return requirement which meets the ALTAIR top-level science requirement. Assumptions relevant to the LGS spot size are a low to medium seeing parameter r_0 = 17 cm @589 nm, a beam quality of 1.5 times diffraction-limited at the output of the laser system and some additional wavefront aberrations added to the beam before it is launched to the sky. The photon return requirement also accounts for a factor of 2 margin on the requirement at zenith. The top-level science requirement in terms of photon return at the primary mirror of the Gemini North telescope is **160 photons/cm^2/s** for a LGS at zenith. This assumes an atmospheric transmission coefficient on the way down T_{atmo} = 0.8. In order to derive the power requirement for the Mauna Kea Laser Guide Star (MK LGS) Laser System, we based our calculations on some slope efficiency (SE) numbers presented in reference [13]. SE numbers enable comparisons between different laser formats in terms of laser/sodium interaction efficiency when the sodium atoms are *not saturated*. The photon return calculation and laser output power requirement calculations based on SE numbers for the Mauna Kea LGS system are detailed in reference [14]. Note that results presented in reference [14] are different from results below because in reference [14] the laser beam was supposed to be diffraction limited and the results did not include any margin.

The photon return requirement translates into the power requirements given in Table 1 for three *examples* of CW and pulsed laser formats by using the following formula [13]:

$$F = SE * (C_S \sec(\theta)) * (T_{atmo}{}^{\sec(\theta)})^2 * P_{launched} / (z \sec(\theta))^2$$

where F is the photon flux at the primary mirror of the telescope in photon/cm^2/ms, SE is the small signal slope efficiency in photon.m^2/ms/W/atom, C_S is the sodium column density in atoms/cm^2, T_{atmo} is the atmospheric transmission from ground to the mesosphere for a zenith angle equal to 0°, $P_{launched}$ is the average laser power in W immediately after the laser launch telescope, z is the sodium layer altitude in meters, and θ is the zenith angle. Though results at zenith only are consistent with the way photon return was derived, we give power requirements for laser guide stars at 0° and 45° zenith angle as well. There is a geometrical increase factor of 1.7 between those requirements which is worth noticing : the intent is to specify high laser power requirements so that the LGS AO system meets its science requirement independently of zenith angle. As section 3 and 4 will demonstrate, the three laser formats investigated below are not the most efficient laser formats in their category for exciting sodium atoms when saturation is accounted for. Note also that assuming no saturation implies assuming no spot size, which is somewhat incompatible with the way the MK LGS photon return requirement was derived [14].

Laser format (example)	Slope efficiency (photon.m^2/ms/W/atom)	Laser output power requirement for a laser head mounted:	
		on the telescope	***off*** the telescope
CW laser Monomode FWHM=10 MHz Circular polarization	0.26 ±0.02	5.4 W @ 0 ° 9.2 W @ 45 °	**7.2 W @ 0 °** 12.3 W @ 45 °
Long pulse laser 100 ns pulse @ 30 kHz rep. rate Phase modulated FWHM=3 GHz Any polarization	0.10 ±0.01	**14.0 W @ 0 °** 23.9 W @ 45 °	18.7 W @ 0 ° 31.9 W @ 45 °
Macro-micro pulse laser 150 µs @ 800 Hz rep. rate 700 ps @ 100 MHz rep. rate Mode-locked FWHM=1 GHz Circular polarization	0.33 ±0.06	4.3 W @ 0 ° 7.2 W @ 45 °	5.7 W @ 0 ° 9.7 W @ 45 °

Table 1 Examples of power requirements for the Gemini Mauna Kea LGS laser system in the no-saturation limit at 0° and 45° zenith angles (assumes $C_S = 2\ 10^9$ atoms/cm^2, z = 90 km, and T_{atmo} = 0.8). Bold numbers will be compared with some results presented in Table 3.

The power requirements in Table 1 are given at the output of the laser i.e. they take into account non ideal transmissions of the beam transfer optics (T_{BTO} = 0.6 - resp. 0.8 -, for a laser mounted *off* – resp. *on* - the telescope) and the laser launch telescope (T_{LLT} = 0.9). *On* the telescope means that the laser would be mounted on the wall of the primary mirror cell, *off* the telescope means that it would be located further down in the pier. There are two sets of requirements per laser format, depending on whether the last stage of the laser system can be mounted on the telescope or not. The difference comes from a higher transmission coefficient between the laser output and the laser launch telescope when the last stage of the laser system is mounted on the Gemini telescope, because in that solution the beam transfer optics include less optical elements.

2.2. Gemini South (Cerro Pachon)

The Gemini South multi-LGSs MCAO system will use five laser guide stars. LGSs will either be generated by one single laser split into several beacons or by several independent lasers. Based upon calculation to date, Gemini South laser power requirements are expected to be about the same *per laser guide star* as for Gemini North. This means that the Cerro Pachon laser system will either be a single laser system producing five times as much power as required by the Mauna Kea LGS system, or it will include as many laser systems as laser guide stars, each laser system producing about the same power as the Mauna Kea laser system.

Among all other effects, saturation will have the biggest impact on laser output power requirement. Saturation of the sodium atoms has to do with the total laser power reaching the sodium layer, the pulse format if the laser is pulsed, the laser bandwidth, the LGS spot size, the sodium atoms cross-section and their density. LGS spot size requirements for LGS AO operation are small enough so that sodium atoms will effectively experience some level of saturation. Therefore we need to understand how saturation impacts photon return for all candidate laser systems. Telle *et al.* [13] show that saturation does not seem to affect the "macro-micro pulse laser" power requirements at least at the power level of interest for the Gemini North LGS system. However, saturation does affect both CW lasers and high repetition rate lasers such as the "CW laser" and "long pulse laser" presented in Table 1. Section 3 studies the effects of saturation and spectral format on continuous wave laser power requirements. Section 4 describes the effects of saturation and temporal formats on power requirements for high repetition rate lasers.

3. POWER REQUIREMENTS FOR CW LASERS (WITH SATURATION)

The Slope Efficiency (SE) number used in Table 1 to estimate the laser power requirement for a 10 MHz monomode continuous wave (CW) laser is derived from a complete theory of sodium excitation by CW lasers [10]. The result includes the effects of optical pumping of the sodium atoms by circularly polarized beams, and other side effects like atomic recoil, geomagnetic field, collisions, dwell time and diffusion. However, the SE number does not take saturation into account, neither can it be used to derive power requirements for lasers with bandwidths larger than 10 MHz. In order to account for saturation and understand the behavior of CW lasers whose bandwidth is larger than 10 MHz, we used the approach presented below. Note that this simple model does not include the effects of optical pumping, atomic recoil, geomagnetic field or spin relaxation. All calculations are made for a LGS at zenith.

3.1. Model

Sodium atoms have a natural linewidth of 10 MHz, related to the D2 transition decay time of 16 ns. Therefore each velocity group of sodium atoms within the Doppler-broadened D2 absorption line has a spectral bandwidth of 10 MHz. Lasers (*any* type of laser really) should have a spectral bandwidth broad enough so that most or all velocity groups of atoms interacting with the laser light are not saturated. The absorption cross-section of the sodium D2 line is modeled as the sum of two gaussian lines whose central frequencies are separated by 1.771 GHz due to hyperfine splitting of the sodium atom ground level. The full-width-at-half-maximum (FWHM) of each peak due to Doppler and hyperfine broadening is $\delta\nu_D$ = 1.1 GHz. The highest peak of the sodium D2 line has a cross-section value of 1.0 10^{-11} cm^2 according to ref. [9] and the lowest peak is the 3/5 of this value (see figure 1). There will be a trade-off between narrowing the laser spectral bandwidth to benefit from maximum absorption cross section and enlarging it to minimize saturation per natural linewidth. If a laser format is close to saturation, the laser spectral bandwidth should be broadened in order to share the laser power between more velocity groups so as to increase the laser global saturation intensity.

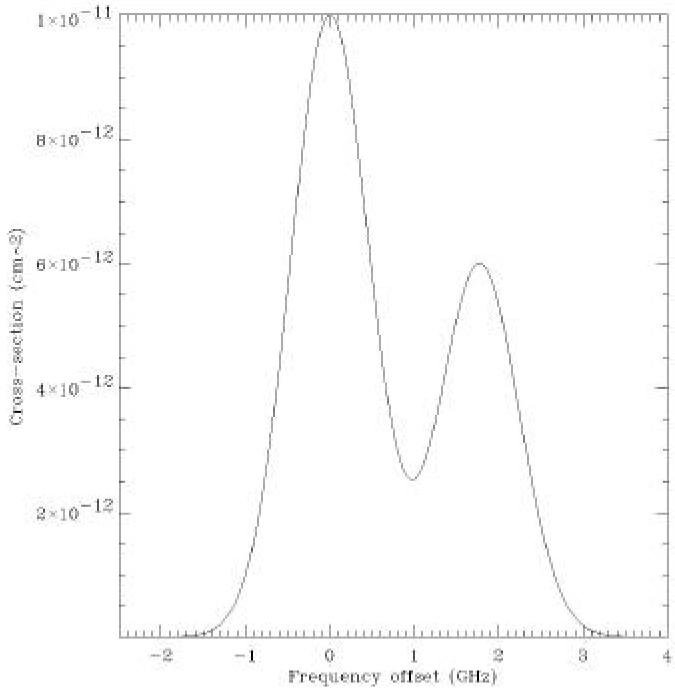

Figure 1 Sodium D2 line

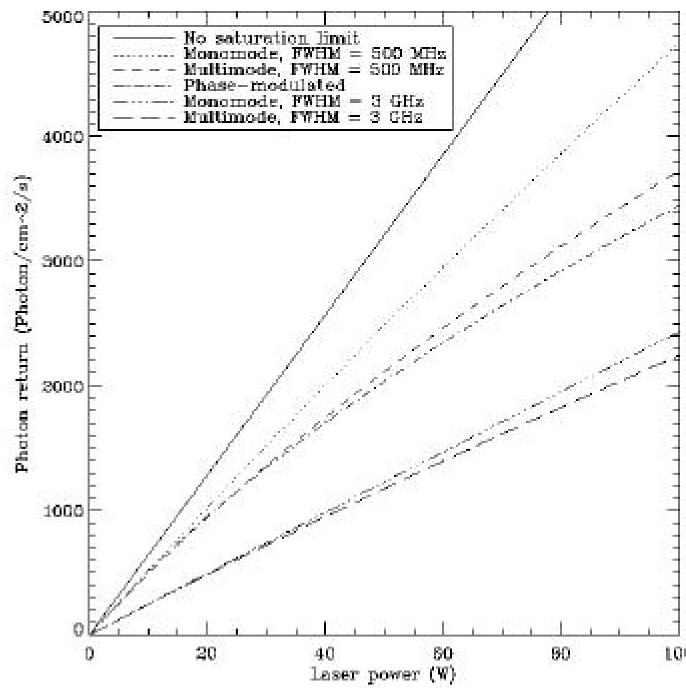

Figure 2 Comparison between photon return models for CW lasers (LGS at zenith). Dotted line: slope efficiency calculation; others: saturation model.

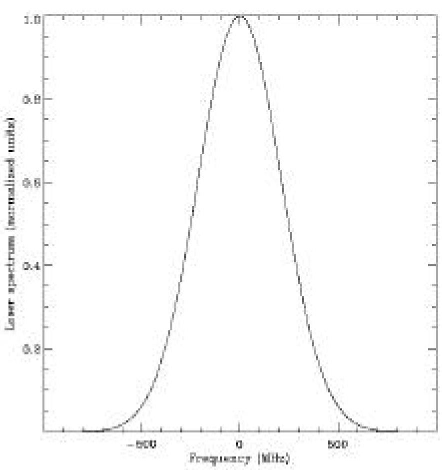

Figure 3a Monomode laser spectrum

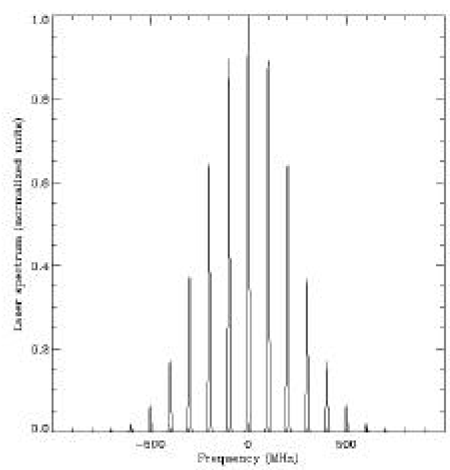

Figure 3b Multimode laser spectrum

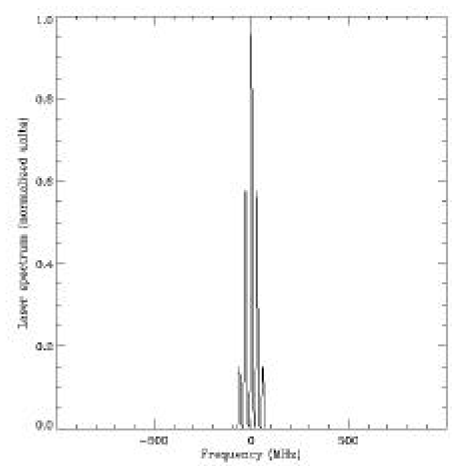

Figure 3c Phase-modulated laser spectrum

In the following, P is the total laser power reaching the sodium layer and $G_L(\nu)$ is the laser spectrum profile whose integral equals 1. In our model, the laser wavelength is centered on the highest peak of the sodium D2 line. We define $I_{NLW}(\nu_1)$ as the laser intensity per natural linewidth:

$$I_{NLW}(\nu_1) = \frac{P}{S} \times \int_{\nu_1 - \frac{d\nu_{NLW}}{2}}^{\nu_1 + \frac{d\nu_{NLW}}{2}} G_L(\nu)\, d\nu$$

where S is the spot surface area and $\delta\nu_{NLW}$ = 10 MHz is the sodium natural linewidth. Assuming that the laser light is circularly polarized, the saturation intensity per natural linewidth is $I_{sat} = 6.4 mW/cm^2$ [15]. For each velocity group of sodium atoms centered at the ν_1 frequency, with a natural linewidth of 10 MHz, the ratio I_{NLW}/ I_{sat} estimates how much those atoms are saturated. The total power absorbed out of a laser of total power P and spectral bandwidth $\delta\nu_L$ by the sodium atoms of column density C_S equals:

$$P_{abs} = C_S \times P \times \int_{-\infty}^{+\infty} \frac{s(\nu_1) \cdot G_L(\nu_1)}{\left(1 + \frac{I_{NLW}(\nu_1)}{I_{sat}}\right)^a} d\nu_1$$

where a = ½ for a laser bandwidth small compared to the sodium natural linewidth of 10 MHz (say up to 100 MHz) and a = 1 for a laser bandwidth large compared to 10 MHz (say above 1 GHz) [16]. Results for laser bandwidths in the 100 MHz-1 GHz range can be interpolated from those lower and upper limit regimes. Finally, assuming that all the laser power absorbed by the sodium atoms is re-emitted over 4π steradians, the flux F of 589 nm photons/cm^2/s collected at the ground is:

$$F = T_{atmo} * \lambda / (h\, c) * P_{abs} / (4\, \pi\, z^2)$$

where T_{atmo} is the atmospheric transmission coefficient, z = 90 km is the sodium layer altitude, c is the speed of light, h is Planck's constant and λ = 589 nm is the sodium D2 line wavelength. Conservatively, we choose not to include the eventual 1.5 enhancement factor due to optical pumping in this final formula [10, 12]. Note that all following results will assume a sodium column density $C_S = 2\ 10^9$ atoms/cm^2.

3.2. Results

The code is written in IDL language. It can compute photon returns from CW laser beacons with either uniform or gaussian spot illuminations. The laser can either be longitudinally monomode or multimode. It can also be single frequency and phase-modulated in order to create a finite number of longitudinal modes alongside the central mode. Figure 2 presents a comparison between different CW laser models in terms of photon return at the sodium layer vs. the laser power reaching sodium atoms. The solid line corresponds to the slope efficiency calculation discussed in section 2. Five laser models are compared: two monomode lasers with either 500 MHz or 3 GHz bandwidths (FWHM), two multimode lasers with the same spectral bandwidth, 10 MHz linewidth longitudinal modes and 100 MHz mode spacing, and a phase-modulated laser. The phase modulated laser spectrum assumes five 10 MHz linewidth gaussian modes separated by 30 MHz with 41% of the energy located in the central mode, 23.5% in adjacent modes (+1) and (-1), and 6% in adjacent modes (+2) and (-2). Figures 3a, 3b and 3c are examples of the corresponding laser spectra. Results in figure 2 assume a gaussian illumination with a 36 cm 1/e^2 intensity diameter. The spot size assumption is related to Gemini specifications (see Table 2). Figure 4 shows the LGS gaussian profile and the spatial saturation parameter $1/(1+I(r)/I_{sat})^{1/2}$ for the 500 MHz bandwidth multimode laser at the 10 W and 100 W power levels. Sodium atoms located in the gaussian core are obviously more saturated than atoms located in the aisles. The existence of non-saturated atoms in a gaussian spot actually explains why overall gaussian profiles can be more efficient in exciting sodium atoms than uniform profiles having the same total power and peak power.

As expected at the 100 W level where saturation dominates, the broad monomode laser format is more efficient than the multimode laser format both in the 500 MHz and 3 GHz spectral bandwidth cases. Also, a 500 MHz bandwidth multimode laser appears more efficient than the example phase-modulated laser due to the narrower bandwidth of the latter. This behavior is related to saturation. Between two lasers whose spectral profiles are different but which have the same total power, the most efficient laser is the one whose power density per natural linewidth of sodium atoms $I_{NLW}(\nu)$ is smaller over the largest frequency range. In other words, each longitudinal mode of a multimode laser saturates sodium atoms more strongly than the corresponding portion of a truly continuous laser with the same spectral envelope. Figure 5 illustrates this

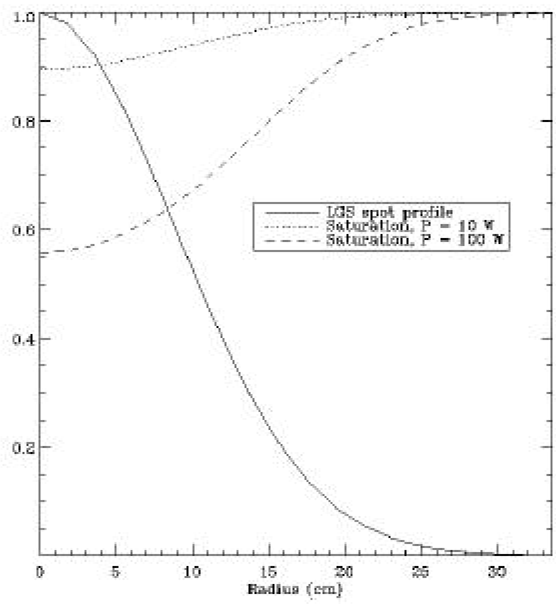

Figure 4 LGS spot gaussian profile and saturation parameter vs. distance to spot center for total laser powers of 10 W (dotted line) and 100 W (dashed line)

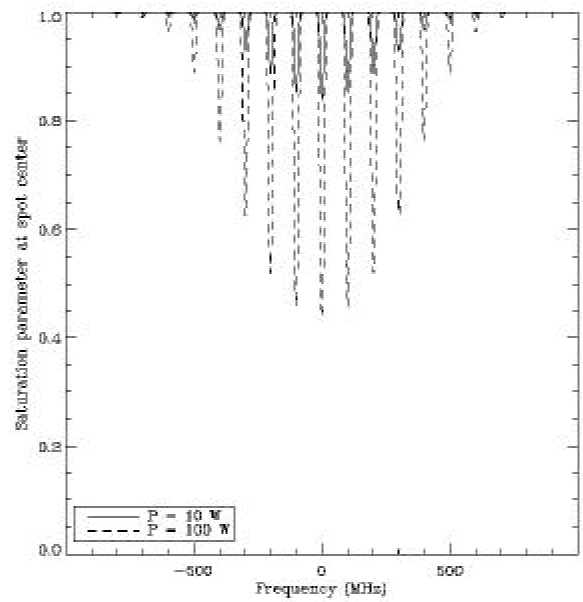

Figure 5 Saturation parameter vs. laser frequency for a multimode laser (FWHM = 500 MHz, mode spacing = 100 MHz) and total laser powers of 10 W (solid line) and 100 W (dashed line)

effect by showing the spectral saturation parameter $1/(1+I(\nu)/I_{sat})^{1/2}$ for sodium atoms located in the gaussian core of the 500 MHz bandwidth multimode laser spot. However we can see that at the 10 W level, monomode and multimode laser models of identical spectral bandwidth give very similar results in figure 2. Differences between spectral laser models vanish when saturation decreases, either due to larger spot sizes or broader laser bandwidths. At this relatively low power level, the LGS spot size and laser bandwidth are the only significant parameters when comparing efficiencies of CW lasers in exciting sodium atoms. This should greatly simplify comparisons when choosing CW laser formats for LGS applications.

Figures 6, 7 and 8 show how the LGS photon return varies with laser powers in the 100 mW to 100 W range, and laser bandwidth in the 1 MHz to 10 GHz range for CW lasers. All curves assume a monomode laser with uniform profile, a spot size of 36 cm (FWHM), and a saturation dependence in $1/(1+I/I_{sat})^{1/2}$. Results in the multimode laser case and/or gaussian spatial profile case were found to be very similar, at the exception of high powers and small laser bandwidth (e.g. above 50 W and below 30 MHz) where saturation dominates. A saturation dependence in $1/(1+I/I_{sat})$ which is more adequate for laser bandwidth larger than 1 GHz [16] also gives very similar results above 1 GHz, and only show significant differences with respect to figure 6 at high power levels (e.g. above 50 W) in the 100 MHz-1GHz range. More importantly for LGS systems currently under interest in IR astronomy, all results are trustworthy at the 10 W level. Uncertainty for those results is estimated to be no more than 20 %. Figure 6 shows that CW lasers with bandwidths below 10-20 MHz are hit by saturation for power levels above 5 W, and the power requirement for those lasers is substantially higher for a given photon return. On the opposite, CW lasers with bandwidths larger than 1 GHz do not suffer from saturation but their power requirement also increases due to poorer efficiency in exciting sodium atoms.

Figure 7 shows the optimum bandwidth CW lasers should have for output powers in the 100 mW to 100 W range (solid line) and the corresponding photon return (dashed line). If a CW laser is used to produce a laser guide star for a given LGS AO system, one can derive the laser output power requirement and optimum laser bandwidth for the laser system (i.e. the bandwidth which meets the LGS AO photon return requirement at the lowest laser power) by using the following:

1. Set photon return requirement at the primary mirror of the telescope for a LGS at zenith assuming a 36 cm FWHM uniform illumination (N in photon/cm^2/s)
2. Calculate corresponding photon return at the sodium layer (divide N by T_{atmo})
3. Use dashed line to find laser power and find corresponding laser bandwidth on solid line (P in Watt and $\Delta\nu$ in MHz)
4. Calculate laser output power requirement (divide P by (T_{atmo}*T_{LLT}*T_{BTO}))

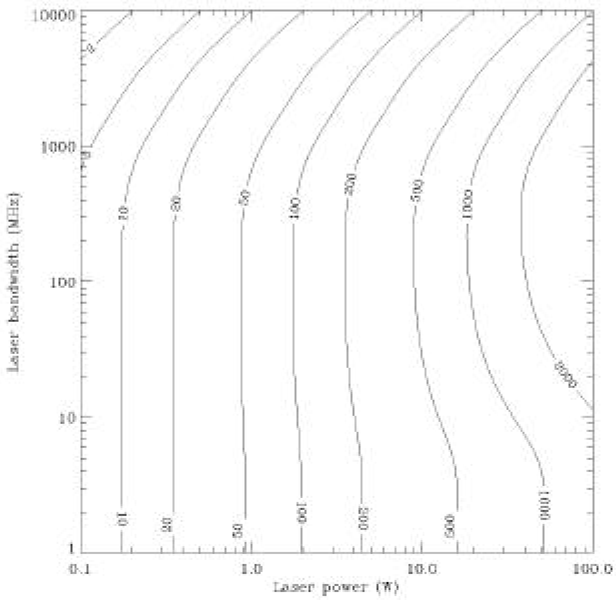

Figure 6 Photon return at the sodium layer in photon/cm^2/s vs. laser power at the sodium layer and spectral bandwidth for CW lasers (LGS at zenith)

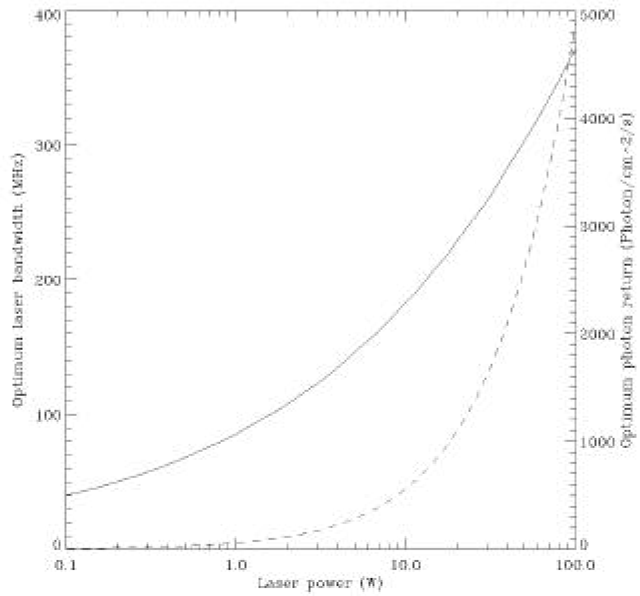

Figure 7 Optimum laser bandwidth (solid line) and corresponding photon return at the sodium layer (dashed line) vs. laser power at the sodium layer for CW lasers (LGS at zenith)

For completeness of the study, it is also interesting to have a look at the photon return values per Watt of laser power, i.e. at the laser/sodium interaction efficiency itself, independently of photon return requirements. Figure 8 shows how efficiency is affected by saturation when laser power increases and/or laser bandwidth decreases. As expected, the laser power is most efficiently absorbed by sodium atoms at low powers (less than a few Watt) when the laser bandwidth equals a few tens of MHz. At higher powers, the efficiency is maximized for laser bandwidth of a few hundreds of MHz. The higher the power gets, the larger the bandwidth has to be in order to balance saturation.

3.3. Gemini laser power requirements for CW lasers

The saturation of sodium atoms depends on the LGS spot size at the sodium layer. We use the following (very conservative) assumptions for the Gemini LGS system:

Laser Launch Telescope diameter	45 cm
$1/e^2$ intensity diameter on LLT primary mirror	30 cm
Laser beam quality	1.5 times diffraction limited
Sodium layer altitude	90 km
LGS spot $1/e^2$ intensity diameter at the sodium layer	36 cm
LGS spot surface	1000 cm^2

Table 2 LGS spot size assumptions for the Mauna Kea LGS system

Note that we choose not to include the seeing contribution into the LGS spot size calculation in order for the LGS AO system to be limited by the laser beam quality on very good seeing nights. An average to low seeing parameter at Mauna Kea is r_0 = 17 cm @ 589 nm. Including the seeing in the spot size calculation would multiply the spot diameter by up to a factor of 2 and the spot surface by up to a factor of 4. This would then translate in a factor of 4 times less saturation than presented in our figures. It is worth noting however than increasing the spot size in order to reduce saturation and thus power requirement would be counter-productive in terms of the AO wavefront sensor (WFS) signal-to-noise ratio optimization.

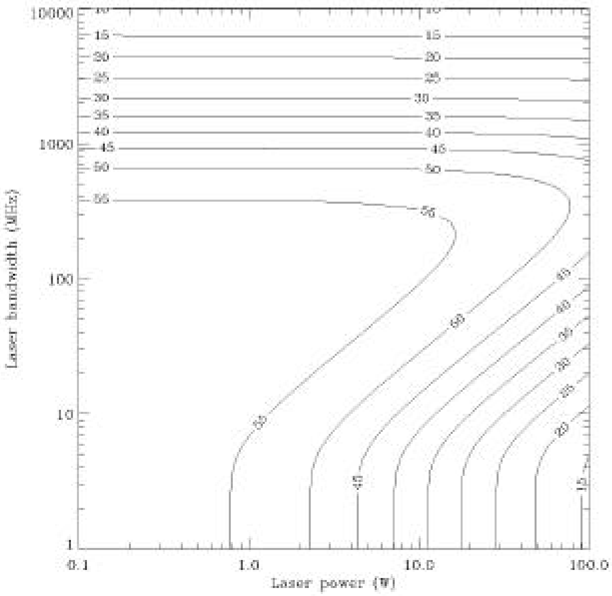

Figure 8 CW laser efficiency (i.e. photon return at the sodium layer per Watt of laser, in photon/cm^2/s/W) vs. laser power at the sodium layer and laser spectral bandwidth (LGS at zenith)

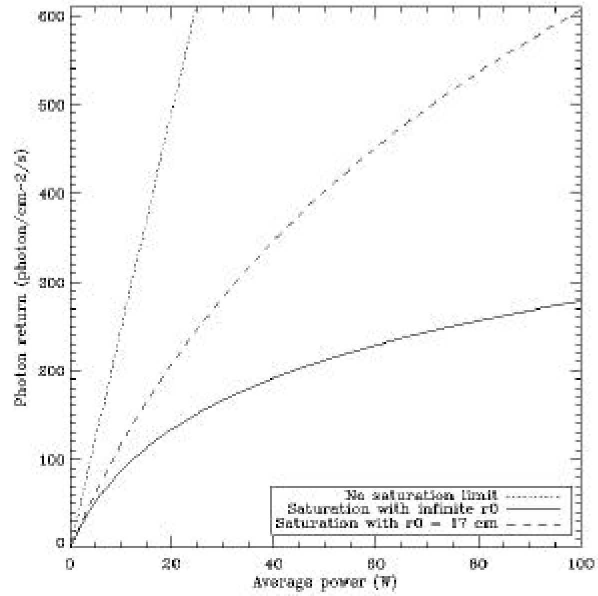

Figure 9 Photon return at the sodium layer vs. laser average power at the sodium layer for a pulsed laser with 100 ns pulses @ 30 kHz repetition rate (LGS at zenith). Dotted line: slope efficiency calculation; dashed line: saturation model, results for bad to medium seeing at Mauna Kea; solid line: saturation model, results for excellent seeing

Assumptions for the Gemini North LGS AO system are T_{atmo} = 0.8, T_{LLT} = 0.9 and T_{BTO} = 0.6 for a CW laser mounted off the telescope. According to figures 6 and 7, the photon requirement of 160 photons/cm^2/s at the primary mirror of the telescope is met by a CW laser with a minimum laser power of 8 W and an optimal bandwidth of 200-250 MHz. More generally speaking, CW lasers with output powers in the 10 W range meet the photon return requirement provided they have a spectral bandwidth in the 50 MHz to 1 GHz range. Note that this is applicable for LGS at zenith. Those power requirements are to be multiplied by a factor 1.7 – 2 when specifying the power requirement for a LGS at 45° zenith angle. Also, optimized laser bandwidth values are likely to shift towards larger bandwidth values.

4. POWER REQUIREMENTS FOR HIGH REPETITON RATE LASERS (WITH SATURATION)

4.1. Model

The Slope Efficiency (SE) numbers presented in reference [13] are useful to compare the relative efficiency of pulse formats in exciting sodium atoms. For instance, providing there is no saturation, two high repetition rate lasers with the same duty cycle have the same slope efficiency. Therefore they are equally efficient in exciting sodium atoms and would provide the same photon return if there were no saturation. However, since pulsed lasers with high repetition rates usually have high peak powers, they are very likely to experience strong saturation, and SE numbers do not allow to assess the laser power requirement for a LGS system such as the Gemini LGS systems. In order to understand how the laser average power, pulse length and repetition rate affect the laser/sodium interaction efficiency, we use the analytical formula given by Milonni *et al*. [9] for "long pulse train" lasers (formula (44) p. 226 of ref. [9]), with the following assumptions. (i) Lasers are assumed to be phase modulated so that their spectrum covers a substantial portion of the D2 absorption profile (FWHM 3 GHz), (ii) the laser pulse length is long compared with the sodium radiative lifetime (16 ns), and (iii) the pulse repetition rate is small enough so that the atoms collisionally relax to thermal equilibrium between pulses. Reference [9] states that collision times in the mesosphere are on the order of 100 µs, and reference [10], based on a semi-empirical approach, gives a calculated collision time on the order of 640 µs. Therefore assumption (iii) might only be true for lasers with repetition rates lower than a few kHz. The calculation also assumes gaussian temporal and spatial profiles for the laser beam, and a laser guide star at zenith.

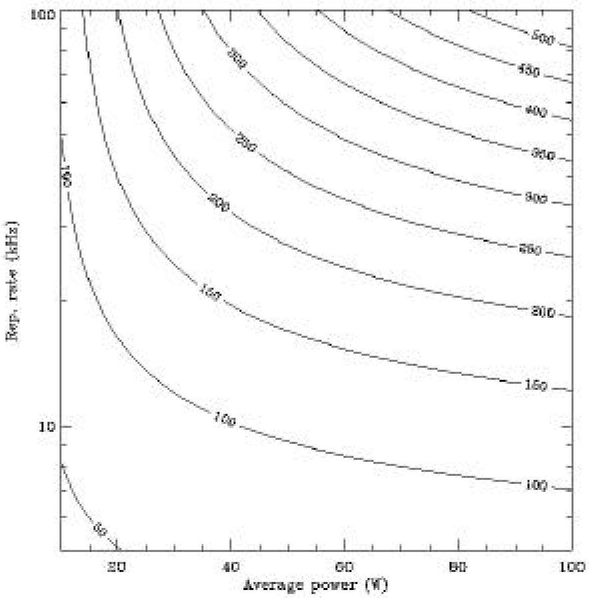

Figure 10 Photon return at the sodium layer in photon/cm^2/s vs. laser average power at the sodium layer and pulse repetition rate for pulsed lasers with 100 ns pulses and high repetition rates (LGS at zenith)

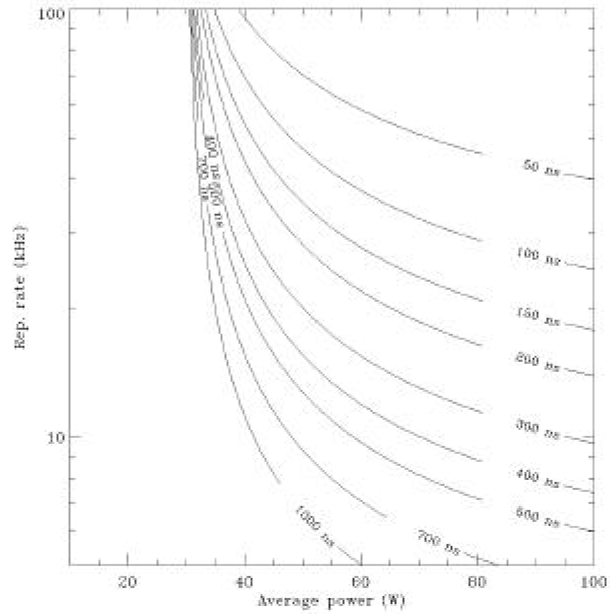

Figure 11 Photon return requirement curves for the Gemini North LGS system vs. laser output power, pulse repetition rate and pulse length. The Gemini North LGS photon return requirement is 160 photon/cm^2/s at the primary mirror of the telescope.

Following [9], the flux F of 589 nm photons/cm^2/s collected at the ground is:

$$F = \frac{1}{32 \ln 2} \times (A\tau_p + 1) \times \frac{T_{atmo} C_S R_p a^2}{z^2} \ln\left(1 + \left(\frac{4 \ln 2}{\pi}\right)^{3/2} \times \frac{T_{BTO} T_{LLT} T_{atmo} P_{laser}}{R_p I_{sat} a^2 \tau_p}\right)$$

where P_{laser} is the laser average output power, τ_p is the laser pulse length, R_p is the pulse repetition rate, $I_{sat} = 5\,\mathrm{W/cm^2}$ is the saturation intensity for such laser formats, $A = (16\,\mathrm{ns})^{-1}$ is the radiative decay rate, a is the spot FWHM at the sodium layer, z is the sodium layer altitude, T_{atmo} is the atmospheric transmission coefficient, C_S is the sodium column density, T_{BTO} is the beam transfer optics transmission coefficient, and T_{LLT} is the laser launch telescope transmission coefficient.

High repetition rate lasers saturate as $\ln(1+I_{peak}/I_{sat})$ with I_{peak} proportional to the laser output power, and inversely proportional to the LGS spot area, the pulse length and pulse repetition rate. Figures 9 and 10 illustrate how saturation impact photon return for an ideal system with $T_{BTO} = T_{LLT} = T_{atmo} = 1$ and a LGS spot of 36 cm (1/e^2 intensity diameter). If a high repetition rate pulsed laser is used to produce a laser guide star for a given LGS AO system, one can derive the laser output power requirement for the laser system by using the same reasoning as described in section 3:

1. Set photon return requirement at the primary mirror of the telescope for a LGS at zenith assuming a 36 cm 1/e^2 intensity diameter gaussian illumination (N in photon/cm^2/s)
2. Calculate corresponding photon return at the sodium layer (divide N by T_{atmo})
3. Assume pulse repetition rate and find corresponding laser power at the sodium layer on figure 10 (P in Watt)
4. Calculate laser output power requirement (divide P by (T_{atmo}*T_{LLT}*T_{BTO}))

4.2. Gemini laser power requirements for high repetition rate lasers

Figure 9 shows how dramatically the laser power requirement is affected when saturation is taken into account for the same “long pulse laser” format as in Table 1 (100 ns pulses @ 30 kHz repetition rate). Within the Gemini assumptions $T_{BTO} = 0.8$, $T_{LLT} = 0.9$, $T_{atmo} = 0.8$, the photon return requirement at the sodium layer is 160/0.8 = 200 photon/cm^2/s on figure 9. This corresponds to a laser output power of 14 W calculated with the slope efficiency model described in section 2. Taking saturation into account and assuming a LGS spot size of 36 cm (resp. 72 cm), the power requirement jumps to 76 W (resp.

32 W). Even in the case of bad to medium seeing condition (r_0 = 17 cm @ 589 nm), the difference in power requirement is non negligible for this particular laser format.

Figure 10 shows how the photon return varies with the laser average power and repetition rate for a pulsed laser system with 100 ns pulses. Within the same Gemini assumptions as above, it appears that such a system cannot meet the 160 photon/cm^2/s photon return requirement for Gemini North if the repetition rate is below about 25 kHz unless it produces more than 100 W of output power. The average output power can only be decreased if the repetition rate is increased. For instance a system producing 100 ns pulses with 35 W average power at 100 kHz pulse repetition rate would potentially meet the requirement. Caution must however be exercised when looking at high repetition rate systems because they do not follow assumption (iii). Therefore, figure 10 is given more as a tool to understand how saturation and pulse length affect photon return than a means to derive absolute power requirement for a given system.

Finally, figure 11 presents a set of photon requirement curves for a range of pulse lengths ranging from 50 ns to 1 µs vs. the laser output power and pulse repetition rate for a LGS at zenith. Each curve is for the Gemini North photon return requirement of 160 photon/cm^2/s. Figure 11 shows that it is probably not possible to reach the photon requirement with less than about 30 W of laser power, whatever the laser pulse length and repetition rate. Almost any power requirement for any laser system with repetition rates greater than 5 kHz and pulse length longer than 50 ns can be derived from figure 12. However these *are not absolute requirements* as the formula above does not include the effects of optical pumping, atomic recoil, geomagnetic field, collisions, dwell time and diffusion. Results are especially subject to caution for high repetition rates where assumption (iii) is not true any more.

Table 3 gives some examples of power requirements that have been derived in sections 3 and 4. As opposed to power requirements presented in Table 1, these numbers now take saturation into account. All power requirements given in Table 3 assume a LGS spot size at the sodium layer of 36 cm and LGS AO observation at zenith. The power requirement for a CW laser is of the same order of magnitude as in the no-saturation limit providing saturation is balanced by a broader laser bandwidth. There is a much larger difference between the power requirement for a 100 ns / 30 kHz repetition rate pulsed laser system because we assume a small spot size which in turn leads to high levels of saturation for a laser with high peak power.

Laser format (example)	Laser temporal and/or spectral characteristics	Laser output power requirement for a laser head mounted:	
		on the telescope	***off*** the telescope
CW laser	FWHM = 200-250 MHz	-	**8 W @ 0 °**
Long pulse laser	100 ns pulse @ 30 kHz rep. rate FWHM=3 GHz	**76 W @ 0 °**	-
	500 ns pulse @ 50 kHz rep. rate FWHM=3 GHz	60 W @ 0 °	-
	1000 ns pulse @ 5 kHz rep. rate FWHM=3 GHz	33 W @ 0 °	-

Table 3 Examples of power requirements for the Gemini Mauna Kea LGS laser system assuming saturation and a 36 cm spot size at zenith. Bold numbers can be compared to bold numbers presented in Table 1.

5. CONCLUSION

This paper describes the steps that we followed to calculate the output power requirements of laser systems used for sodium LGS AO operation and the optimized parameters of some candidate lasers. Those results are presented in Table 3. The steps that we followed are schematically:

1. Assume laser beam quality, seeing parameter, optical and atmospheric transmission coefficients
2. Derive LGS spot size at the sodium layer
3. Determine LGS limiting magnitude and translate into photon return at the primary mirror of the telescope in photon/cm^2/s

4. Use slope efficiency numbers to estimate range of output power requirements for candidate laser systems depending on their temporal, spectral and spatial format
5. Assess saturation impact on photon return and optimize laser parameters such as spectral bandwidth or pulse format to balance saturation and find the lowest laser power requirement

The simple models presented in section 3 and 4 enable the comparison of laser system efficiencies in two subcategories of candidate laser systems, e.g. continuous wave lasers and high repetition rate pulsed lasers. The power requirements calculated with a simple model of saturation of the sodium atoms are compared to those presented in section 2 where saturation is not included in the model. It appears that saturation is a key parameter when assessing the laser efficiencies in exciting sodium atoms. As expected, power requirements accounting for saturation are higher than power requirements derived in the no-saturation limit. They can be either slightly higher ("CW laser" case) or much higher ("Long pulse laser" case) especially if saturation is high due to small spot size assumptions. Finally, we derived examples of power requirements for the Gemini North and Gemini South laser systems when the LGS is at zenith. These numbers are expected to increase by a factor of 1.7 to 2 for LGS AO systems specified to work at 45° zenith angle and at the same performance level.

6. ACKNOWLEDGMENTS

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