The Palomar Laser Guide Star Flux

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1. Observed LGS flux

We have gathered photometric observations of the Laser Guide Star on each LGS engineering night since 16 April 2006. These data typically consist of one or more images of the LGS taken with the AO acquisition camera after all spot size and power optimization are complete, with a matching "detunned" (off the resonant scattering wavelength) image for scattered light subtraction. We the refocus the acquisition camera to infinity and take two dithered images of a standard star of approximately the same magnitude. All images were taken through a Johnson V filter, with the optimum "flat map" on the deformable mirror.

The images were analyzed using an automated IDL script which subtracts the relevant background or sky frame, locates the brightest object in the frame, and runs simple aperture photometry routine with background subtraction to derive the total number of photocounts per second recorded in each. A 6" aperture was used for both the NGS and LGS. The camera's photometric zeropoint was derived from the NGS observations on each night, and used to determine the magnitude of the LGS (see Table 1). Erratic behavior of the acquisition camera on 6/14/06 (see Section 7) led me to throw out the photometric calibrator data and use the mean zeropoint of the other clear nights on that date.

UT Date	Landolt star	V (mag)	Z (mag)	Conditions
4/16/06	107-970	10.94	19.33	clear
6/14/06	109-537	10.35	*19.44*	clear
6/15/06	106-700	9.79	19.46	clear
7/12/06	111-775	10.74	19.55	clear
7/13/06	112-275	9.91	19.42	clear
7/14/06	108-551	10.70	19.30	high smoke

Table 1: Photometric calibration on each night. The zeropoint magnitude, Z, is the V magnitude of a star which would produce 1 DN s^{-1} on the detector (at airmass 1.20 in this case.)

The laser guide star magnitude and flux at zenith on each night included in this study are shown in Table 2. No correction was made for the lower airmass of the LGS with respect to the calibrator star (at most this would lead to an overestimate of the LGS flux of 5%). The effective V magnitude was then converted to a photon flux above the atmosphere, more appropriate to a monochromatic source. On most nights, the laser power at the CSFL exit shutter was measured within 5 minutes of the photometric observation, and both the measured power and flux per Watt are included in the table.

UT Date	Power (W)	Pol.	Filename	V (mag)	ph s^{-1} cm^{-2}	ph s^{-1} cm^{-2} W^{-1}
4/16/06	5.0	linear	laser2	10.43	59.2	11.85
6/14/06	7.0	circular	laser_pol_right_6_7535	9.78	107.9	15.42
6/15/06	7.5	circular	laser_tune_-22.5_2_7	9.65	121.4	16.19
7/12/06	6.2	circular	laser5_05_11950	10.17	75.2	12.13
7/13/06	6.7	circular	laser_tuned3	9.85	101.4	15.13
7/14/06	6.4	circular	laser5_11300	10.04	85.0	13.28

Table 2: Laser guide star brightness on each night. Where multiple images were available, the most representative was included here.

2. Consistency with predictions

The expected flux of the laser guide star at the top of the atmosphere, per Watt of laser power produced, can be computed using a modification of the formula for return flux from d'Orgeville *et al.*[1]:

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

where F / P_{laser} is the return flux at the top of the atmosphere per Watt of laser power produced, in ph s^{-1} cm^{-2} W^{-1}, SE is the slope efficiency (SE = 3.3 x 10^2 in these units for a 1 GHz bandwidth circularly polarized marcopulse-micropulse laser), C_S is the sodium column density, T_{atmo} is the atmospheric transmission at zenith, T_{BTO} is the transmission of the beam transfer optics and launch telescope, z is the altitude of the sodium layer above the observatory in meters, and θ is the zenith angle.

Reasonable estimates for the inputs to this formula during the experiments described here are as follows:

C_S = 2 x 10^9 atoms cm^{-2}
T_{atmo} = 0.80
T_{BTO} = 0.25 (estimate from 7/13/06 BTO transmission experiment)
z = 8.8 x 10^4 m
$\theta = 0$

Using these parameters, we would expect the flux per watt of laser power to be:

$$F / P_{laser} = 17.0 \text{ ph s}^{-1} \text{ cm}^{-2} \text{ W}^{-1}$$

This value is slightly higher than the average measured over the past 3 months (14.43 ph s^{-1} cm^{-2} W^{-1} for circularly polarized light, see Table 2). My first conclusion is therefore that the LGS magnitude observed in the acquisition camera is nearly consistent with theoretical predictions, given our current knowledge of the laser and beam transfer optics, and assuming a typical value of the sodium column denstity. The range of guidestar magnitudes which we measure is also entirely consistent with the expected temporal variations in the sodium column density of a factor of two[2].

3. High order wavefront sensor flux predictions

The LGS flux measured above can be converted to an expected flux in the high-order wavefront sensor by including the atmospheric, telescope, AO system, and wavefront sensor losses. Most of these losses are suffered equally when the wavefront sensor is locked on a star in NGSAO.

The HOWFS photometric zeropoint in NGS mode was computed from observations of HD 154791, a V=7.64 M2III star observed by B. Cameron at 05:26-05:32 15 July 2006 UT. The HOWFS recorded an average of 4738 DN $subap^{-1}$ at 500 Hz framerate, leading to a photometric zeropoint of Z = 23.58, quite close to the value of Z = 23.63 used in the AO error budget spreadsheet (version 1/7/2005). The seeing, as recorded by the DIMM, was 0.75 at the time, leading to a negligible amount of light intercepted by the 2.6" square field stop. While the LGS observations were not made in identical atmospheric conditions, night-to-night variations in atmospheric opacity should lead to errors of <10%.

If the dichroic reflective spot has the same reflectivity at 589 nm as the aluminized spot does to broadband light, then the subaperture flux C in DN $subap^{-1}$ s^{-1} will be

$$C = 10^{(-0.4\,(M - Z))} * (B_V / B_{HOWFS}) * \mathrm{ERF}(\, d / (2\sqrt{2}\,(w / 2.35)))^2$$

where M is the guidestar magnitude, B_V is the bandwidth of the Johnson V filter (89.3 nm), B_{HOWFS} is the effective bandwidth of the unfiltered HOWFS (~450 nm, poorly constrained), d is the field stop linear size in arcseconds, and w is the full-width at half maximum of the guidestar. Predictions for the HOWFS flux on each of the nights included in this study are compared to the observed values in Table 3.

UT Date	V (mag)	FWHM (")	Predicted flux (DN subap^{-1} s^{-1})	Measured flux (DN subap^{-1} s^{-1})
4/16/06	10.43	4.03	11000	17500 (11:45 UT)
6/14/06	9.78	3.04	30800	15000 (09:05 UT)
6/15/06	9.65	3.08	34100	15000 (07:25 UT)
7/12/06	10.17	2.89	23100	N/A
7/13/06	9.85	3.17	27200	8000 (10:40 UT)
7/14/06	10.04	3.23	22200	7500 (06:50 UT)

Table 3: Predicted and measured subaperture flux for the LGS. With one exception, he measured flux is 2-3 times lower than that predicted from the acquisition camera photometry. The FWHM listed in the third column is that measured in the image listed in Table 2, generally taken ~1 hr before the flux measurement.

4. Where did all the 589 nm photons go?

We are loosing the vast majority of the 589 nm light returning from the laser guide star somewhere between the dichroic reflecting spot and the HOWFS detector. The most likely culprit would appear to be the reflectivity of the dichroic spot at 589 nm, but other candidates include a serious optical misalignment of the HOWFS when focused at ~90 km altitude, and unexpected behaviour of the CCD-39 detector illuminated by pulsed, monochromatic light.

5. Conclusions

The flux of the Palomar LGS, as recorded by the AO acquisition camera, appears to near that predicted by theory, given the poor transmission of our beam transfer and launch system (~25%). There is no need to hypothesize that the laser bandwidth is too large, or the sodium column density unusually low, to explain our observations to date.

However, very little of this light which reaches the acquisition camera actually gets detected by the HOWFS detector when reflected off of the dichroic reflecting spot, even when taking into account the known effect of vigneting by the 2.6" field stop. Resolving this puzzle should clearly be a very high priority, as it may well allow us to close the HOWFS loop on the LGS at 500Hz, even without improvements to the BTO transmission or spot size.

6. Appendix A

An instrumental calibration value not directly related to this study but useful for planning future engineering experiments is the photometric zeropoint of the HOWFS when observing a broadband source such as a star with the sodium dichroic reflective spot. Analyzing the HOWFS telemetry taken on HD 123408 (V=7.01, K0) at 4:04, 14 July 2006 UT, I find:

$$Z_{dichroic} = 20.22$$

Comparing this value to the HOWFS photometric zeropoint using the aluminized reflective spot, I find that a star 3.36 magnitudes brighter is needed to reproduce the expected level of AO performance when using the dichroic spot on an NGS.

7. Appendix B

While analyzing these data, I uncovered intermittent erratic behavior of the AO acquisition camera. For example, two 5s integrations were taken of the photometric standard star Landolt 109-537 on 6/14/06 UT under clear conditions, ~15s apart. The first frame (landolt109_1.fits) recorded a total of 12425 DN from the star, while the second (landolt 109_2.fits) recorded 31180 DN. The sky values are essentially equal (17.2 and 17.6 DN pixel^{-1}) and the standard deviation of pixel values on the sky was higher in the first frame than the second (1.37 and 0.96 DN, respectively). I could find no simple explanation for this behavior, and was forced to throw the data out.

A more common occurrence was incorrectly reported integration times in the image's FITS headers (always by a factor of two). This was confusing, but could generally be disentangled by consulting the night log, or comparing sky background values.

[1] d'Orgeville, C., F. Rigaut, and B.L. Ellerbroek, 2000. LGS AO photon return simulations and laser requirements for the Gemini LGS AO program. *Proc. SPIE* 4007, 131-141.

[2] Ge, J., and 9 others, 1997, Mesosphere sodium column density and the sodium laser guide star brightness. Proc. ESO workshop on Laser Technology for Laser Guide Star Adaptive Optics, Garching, ed. N. Hubin, 55, 10.