Laser Guide Star Radiometry From Several Off Axis Locations

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Abstract: Five telescopes with apertures of 60mm to 300mm and four different sensors were setup at off axis ranges of 60 meters, 800 meters, and 7.2 km from the laser guide star projection telescope attached to the 3 meter Shane Reflector at Lick Observatory. Results will be discussed in which an all night data collection was used to compare irradiance (ph/cm^2/sec) of the laser guide star from each location and sensor. The dynamic behavior observed and measured profiles will also be shown. In addition an evaluation of the irradiance collected from the Lick Guide Star Shack Hartmann sensor will be compared to our off axis sensors.

1. Introduction

The Advanced Technology Center of Lockheed Martin has been interested in understanding the radiometry associated with the use of a laser guide star for adaptive optics correction of images or beam clean up for laser propagation. With that overall problem in mind the laser guide star (LGS) project included several subsidiary goals.

- Obtain LGS images at several locations and at various ranges from the laser transmitter
- Demonstrate ability to detect the LGS from off axis locations using only the latitude, longitude, and altitude of the sensor location and transmitter location
- Investigate the dynamic behavior and geometry of the LGS
- Experimentally investigate the LGS radiometry for on axis vs. off axis cases.
- Develop a model to predict LGS behavior for other situations

2. Approach

Lick astronomers would hold the LGS illuminator laser at a fixed elevation of 90 degrees throughout our tests. This would give a consistent pointing azimuth and elevation for each off axis site. Telescope apertures, focal lengths, sensors and locations were chosen to minimize the risk of not obtaining adequate SNR due to either field of view (FOV) or sensitivity issues. For this first test, three locations, five telescopes, and four sensors were selected. The first site chosen was 200 feet from the Lick 120 inch Shane telescope, where the LGS transmitter was located. The second site was located approximately ½ mile (800 meters) 254 degrees WSW of the transmitter next to the Lick 40 inch dome housing the 40 inch Nickel reflector, and the final site located at Grant Park, about ½ way up Mt. Hamilton at an altitude of 2100 ft and a distance of 4.5 miles (7.2 Km) 268 deg west of the laser transmitter.

The site next to the transmitter was chosen to insure detection of the LGS, regardless of possibly low SNR due to low laser power or atmospheric effects. The sensor chosen was a digital single lens reflex (DSLR) camera from Canon attached to an 80mm aperture which allowed a large FOV to ensure capture of the LGS and Rayleigh scatter. The Rayleigh scatter was used as a simple, foolproof, method to locate the LGS. This small telescope and sensor was also chosen as an easily portable instrument which was transported between the transmitter location and the ½ mile location several times during the tests.

The ½ mile location was chosen to be sufficiently off axis to allow separation of the Rayleigh scatter from the LGS, but not so far removed that the Rayleigh could not be easily seen. Radiometry considerations required this separation. However, as in the first location, this also allowed the simple technique of scanning the telescope up the beam until the LGS could be seen as a separated , elongated spot above the Rayleigh beam. At the same time this allowed a test of the “blind pointing” scheme in which the known position of the telescope is used to calculate the correct az/el to be used to point to the LGS. This will be explained below. The final location of 4.5 miles from the transmitter resulted in a suitable change in altitude (2200 ft), off axis angle (~ 5 deg), and slant range to obtain reliable radiometry images of the LGS with no Rayleigh, and an adequate test of the pointing to the LGS using only the location of telescope and transmitter. A separate result of this location was to determine the illuminance of the LGS from this off axis location compared to the other locations.

As stated previously, apertures, focal lengths, and sensors were chosen based on FOV’s and SNR. Positioned at the ½ mile location was a 12 inch (300 mm) telescope and Atic16ic sensor, and a 5 inch (120 mm) telescope and DSI Pro sensor. The 120mm aperture and mount gave us the ability to track the guide star when Lick performed their usual adaptive optics image correction experiments. The 12 inch ensured adequate SNR , but had a smaller FOV. The 4.5 mile location used an 8 inch aperture(200mm) and 60mm aperture to insure capture of the LGS at this range. A similar sensor as the 120mm telescope, a DSI X, was used on both apertures . This would give us a good radiometry comparison for the two locations and three different telescopes. In addition, the 60mm aperture and 350mm focal length gave a FOV which was chosen to cause the LGS to cover an angular extent of about ¾ of the FOV. The 8 inch FOV only covered a portion of the LGS, but was sufficient to get profiles of regions of interest.

3. Details of the setups

In the fig. 1 below are shown photos of the telescopes, mounts, and sensor locations.

Fig. 1 Telescopes, mounts, and sensors. Clockwise from top left: 120mm at 40 inch , 80mm at 120 inch, 12 inch next to 40inch Dome, 8 inch and 60mm at Grant Park

Fig. 2 is a schematic layout of the locations of the telescopes and sensors relative to the LGS transmitter attached to the 120 inch Lick telescope. The specifications of the laser transmitter are listed in Table 2. During the test the average power was held at 7.5 watts, with a projected energy of 0.58mj/pulse and repetition rate of 13 Khz. The laser divergence was estimated at 7 urad , based on a measured spot size of 2 arc sec for the LGS. This indicated that the beam was nearly diffraction limited, as the 1/e Airy diameter for a diffraction limited beam at 589nm would be approximately 5.8 urad. Based on this measurement we would expect the laser divergence, and consequent LGS spot will be driven by the atmospheric ro conditions rather than the beam quality of the laser.
Table 1 summarizes the details of the sensors used in each aperture as well as the focal lengths and resultant FOV's.

Table 1 : Details of telescope apertures, FOV's, and sensors

aperture (mm)	focal length(mm)	f/#	sensor	focal plane	pixel	FOV (deg)	location
80	400	5	Cannon D20,12bit	2336x3504 15mm x 22.5 mm	um 6.4 x 6.4	2.1 x 3.2	120", 40"
60	350	5.8	DSI X,16bit, 1 e-	582 x 752 4.8mm x 6.5 mm	8.3X8.6	.79 x 1.06	Grant Park
120	600	5	DSI,16 bit,2 e-	492 x 510 3.7mm x 4.9 mm	7.5 x9.6	.35 x .47	40"
200	1260	6.3	DSI X,16bit,1e-	582 x 752 4.8mm x 6.5mm	8.3 x 8.6	.21 x .29	Grant Park
300	841	2.76	Atik16ic,16bit,7e-	494 x 659 3.7mm x 4.9 mm	7.4 x 7.4	.25 x .33	40"

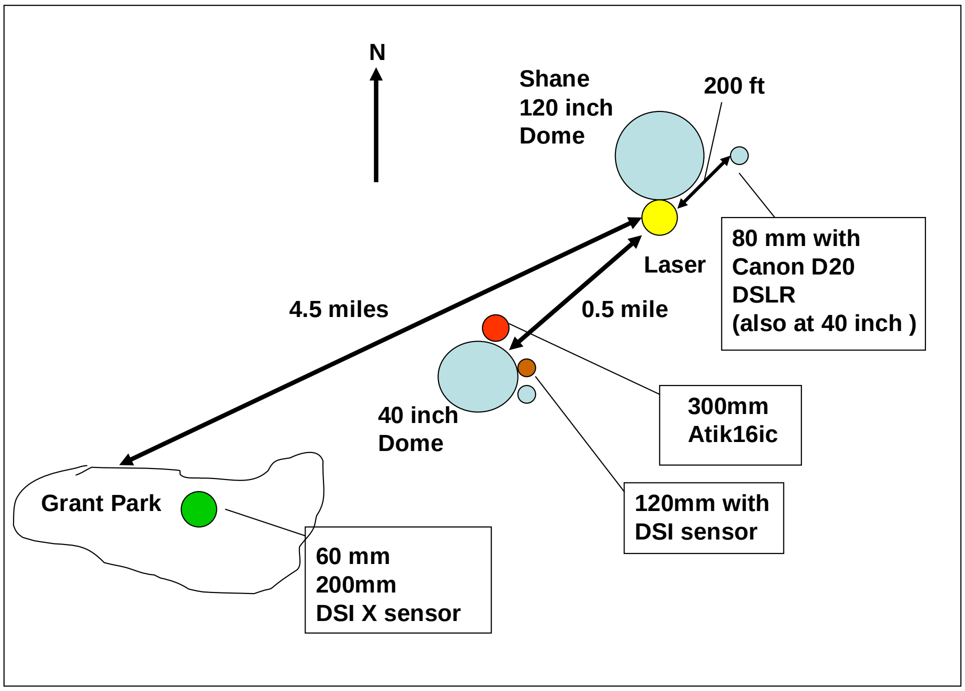

Fig. 2 Location of telescopes and sensors

Table 2 : Details of Guide Star Laser Illuminator

Pulse width ………………. 150nsec
Rep rate……………… 13 kHz
Energy/pulse 0.58 mj/pulse @ 7.5 w ave power (1.15mj @ 15 watt max)
Ave power : ……………… 7.5 watt during our tests
Laser divergence….. 7 urad when guider camera showed
2 arcsec spot(ie, ro estimate)
Polarization : ……………… Linear
Laser beam size
At exit aperture………………25 cm

1/e Airy radius diff limit divergence = 1.22 λ/D = 2.9 urad

Full angle = 5.8 urad
Assuming 7 urad beam divergence → M^2 ~ 1.2 ro > 25 cm
Appears laser spot is ro limited not BQ limited

4. Guide Star images, profiles, and geometric measurements

In this next section we will summarize the results obtained from each of the telescopes and sensors, showing the collected Laser Guide Star images as well as representative one dimensional irradiance profiles. These images were the primary means of estimating captured photon flux at each location.

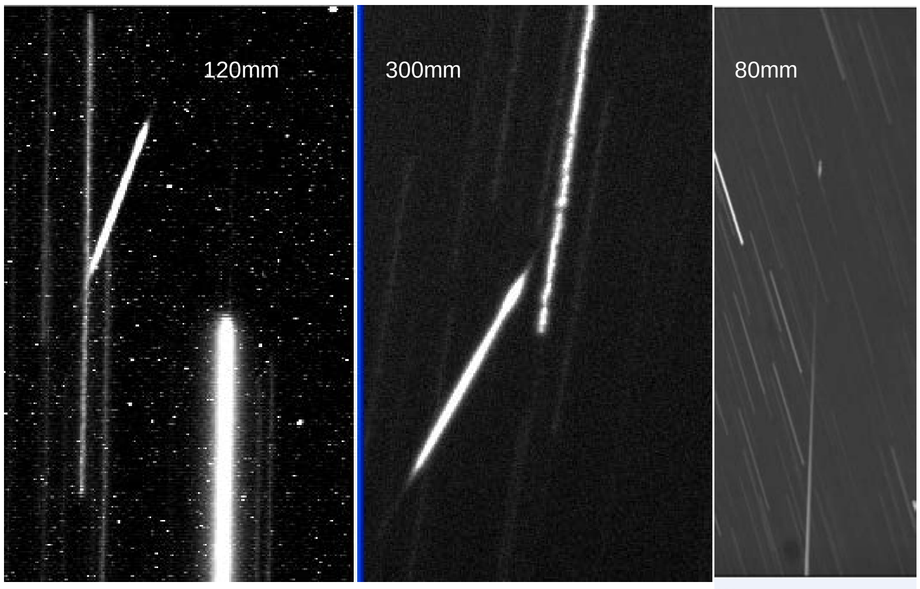

Fig 3: Laser Guide Star images at 40 inch location ½ mile (0.8km) from laser

Fig. 3 is a montage of images from the 80 mm, 120 mm, and 300 mm telescopes obtained at the ½ mile site at the 40 inch Lick dome. Differences in FOV's are clearly evident, with the 80mm , 2.1 deg x 3.2 deg DSLR easily seeing the Rayleigh scatter at lower altitudes and the LGS elongated image at higher altitudes. The streaks alongside the LGS images are star trails due to the exposure times used for each image. These streaks were also used to verify FOV's by calculating the expected sidereal rates at these elevations. Table 1 gave these calculated, and verified field of views. Also of note in the images is the clear distinction between the Laser Guide Star image streak, compared to the star streaks. The star streaks consist of parallel lines at a constant angle with respect to the LGS, based on the geometry of the optics used to capture the images. As shown in figure 1, the 80 mm telescope was directly coupled to the DSLR camera, while the 120mm and 300mm used a right angle mirror to allow images of the LGS at the 89.6 deg elevation used in these tests. The clear difference in the LGS and star streaks was fortuitous as we were concerned that if longer exposures were needed to capture the LGS image, star trails might overwhelm the LGS image. This was especially a concern at the Grant Park location, were we anticipated needing 2 minute, or larger exposures. Due to this obvious difference, in all cases, the LGS was easily distinguished from star streaks.

The other distinguishing characteristic that became apparent as the tests proceeded, was the hot spot at the top of the LGS image seen in the 120 mm and 300 mm images. We investigated this further, as shown in the next images and profiles.

The top two images in Fig. 4 show the laser guide star image obtained from the 60 mm aperture, along with its one dimensional profile. The bottom figure is a radiometrically calibrated image from the 300mm telescope at the ½ mile location. These exposures at the two locations clearly show the same high narrow peak at the higher altitude.

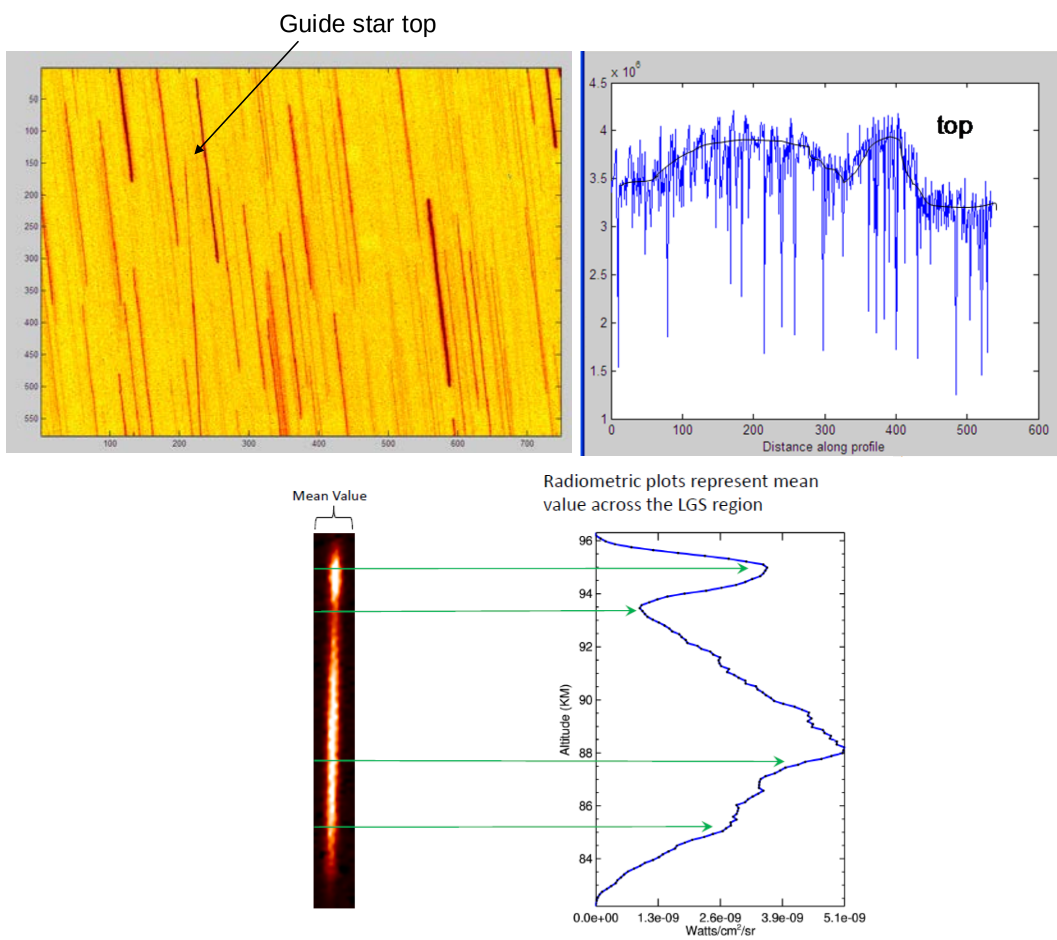

Fig. 4 Laser Guide star image and profiles collected by 60 mm (top) and 300mm apertures (bottom)

Fig 5 is a comparison of the profiles obtained in the 12 inch and 60 mm system at the ½ mile and 4.5 mile locations. Evident is the asymmetry of the guide star profile as well as a change in irradiance at different times. The 12 inch LGS profiles show a broad peak at the lower elevation followed by a much sharper distribution at the higher altitude. Although this general profile maintained in these two regions, the maximum intensity changed from a maximum at the lower elevation at 3:09-3:15 am to the maximum at the higher elevation peak at 2:13 am. Evidence from other profiles showed once this shift occurred at approximately 2:15 am, the top of the guide star maintained this hot spot. Although the two regions are still seen at the 4.5 mile location, from this vantage point it appears that the broad distribution of the lower elevation becomes further broadened while the hot spot distribution seems to maintain its smaller width. Shown in figure 6 are the results of an algorithm used to predict pointing for each of the telescopes based on their latitude, longitude and altitude. Note that for the 90 deg, fixed elevation, used for the LGS illuminator, the ½ mile location required an elevation of 89.6 deg and the 4.5 mile location required an elevation of 85.6 deg. This difference in elevations allowed measurement of the LGS geometry which is summarized in fig. 7.

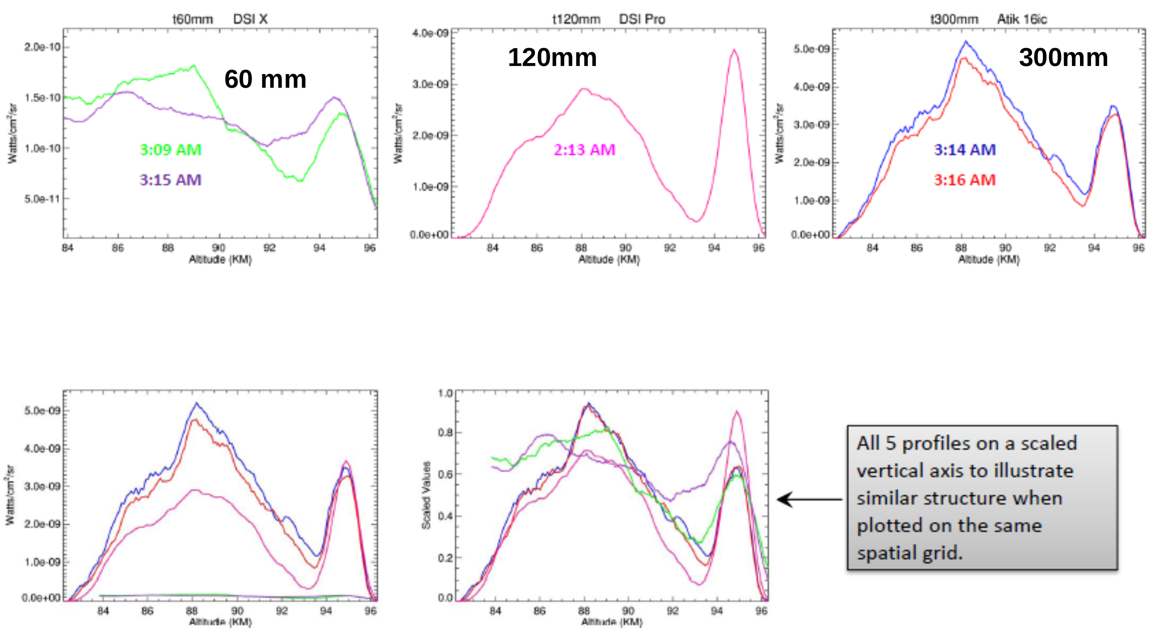

Figure 5 Laser Guide Star profiles from 12 inch system at ½ mi and 60 mm system at 4.5 mi

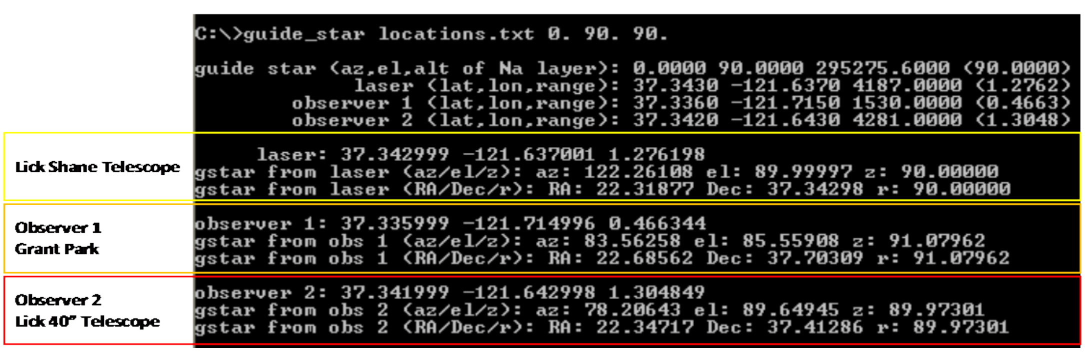

Fig 6 Program used to predict az and el pointing to laser Guide Star from Grant Park and 40 inch locations

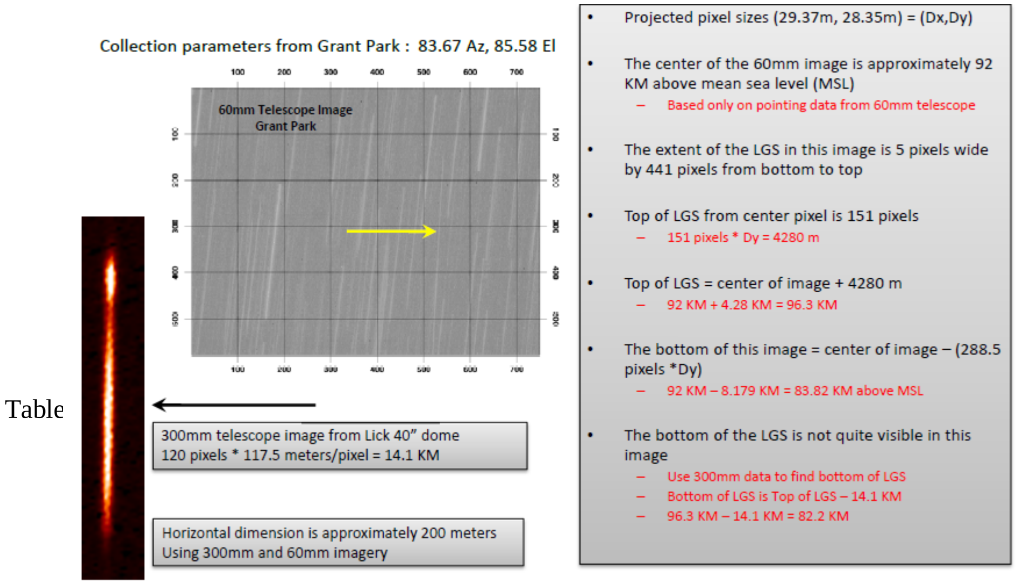

Fig. 7 Using 300mm and 60 mm telescope images shows LGS dimension ~ 200m x 14.1 km

Fig 7 is a summary from the images and profiles obtained at the ½ mile and 4.5 mile locations. The min to min irradiance of the LGS distribution was determined to be 14.1 km in vertical extent and 200m in a direction perpendicular to the length. The altitude of the center of the distribution was determined from the pointing of the 60 mm and 200 mm telescope images at the 4.5 mile location and was found to be approximately 92 km. The scale of the 60 mm profile and 120 mm profiles can be compared based on the calibration of the pixel sizes of the images. The scale for the 60 mm profile, as shown in fig. 4, shows the location of the peaks of the broad and narrow distribution at 88 Km and 95 Km for an approximate separation of 7 km. This separation seemed to be maintained throughout the data collection from 12 midnight to 6 am.

5. Sensor Calibration

Before using the images, or profiles, to obtain estimates of the photon flux captured by the telescopes, it is necessary to calibrate each of the sensors to determine the gain of the A/D circuits in terms of e-/count and based on the QE the resultant photons /ct. Two methods were used as a cross check on each other. Known stars, with a known color temperature, and at elevations close to the guide star location were recorded at several integration times. A blackbody spreadsheet model is used to predict the star exoatmospheric irradiance in watts/cm^2/um and using the energy (j/ph) at 589 nm and integration time this is converted to photons/cm^2/sec expected at the telescope aperture. An estimate of each telescope transmission is then made to determine the expected irradiance on the sensor. This number of expected ph/sec at the sensor is then compared to the cts/sec obtained for the star to obtain the gain in photons/ct.

The results of this calculation is the following expression

$$D\varphi/dt = 1.03\ e7 * 10^{(-.4mv)} * qe*Tatm^{secz} * Tloss * \Delta\lambda(um) \quad ph/cm^2/sec \quad (1)$$

Where mv is the visible magnitude, qe the quantum efficiency, Tatm the atmospheric transmission, z the zenith angle, and $\Delta\lambda$(um) the bandwidth of the sensor or filter used. This is multiplied by the unobscured aperture in cm^2 to obtain the ph/sec expected from the star.

The second method involved an LED operating at 589 nm. and large divergence. The LED was positioned at sufficient distance to allow a beam footprint of close to 1 meter at the location of the detectors. A calibrated detector was positioned just before the sensor to measure the flux in watts/cm^2. Suitable neutral density filters were inserted in the beam path to attenuate the flux to incident levels of a nW and less. Several files were then collected at several exposure times for each sensor which allowed collection of irradiance from minimum detectable to 70% of the full well for each chip. These files were used to obtain cts/sec vs. photons/sec to obtain the gain in photons/count.

The results of these two calibration techniques for the 12 inch detector (Au = 661cm^2), the Atik16ic, was a msec test with Altair (mv~ 0.8) at 80 deg elevation (H_λ = 1.9 e-12 w/cm^2/um) of 16 ph/ct , a mag 11.3 star with 30 sec exposure and 85 deg elevation yielding 22ph/ct, and an LED test with the same detector with 1 nW and 20 sec exposure giving 20.6 ph/ct. These three were averaged to give a reported result of 19.5 ph/ct which is rounded off to 20 ph/ct. Similar tests were completed for the other sensors with the results as follows:

Atik16ic	20 ph/ct
DSI Pro	3.5 ph/ct
DSI X Pro	1.5 ph/ct

6. Results: Measured irradiance of Laser Guide Star

Fig. 8 shows the method used to determine the measured irradiance of the guide star using images obtained in the 300 mm (12 inch) telescope sensor at the ½ mile location. A similar method was used for the 120 mm and 60 mm telescope sensors at the ½ mile and 4.5 mile locations, respectively.

Explained in the figure is the basic technique used. After subtracting a dark exposure from the raw file, a region of interest (ROI) surrounding the LGS image is chosen and separated out to determine the total counts representing the sky background plus LGS image. A smaller region of the ROI, with no stars, is used to obtain the average counts/pixel of the sky. This number is used to obtain a representative sky background for the full ROI which is then subtracted from the signal file to obtain the LGS only counts. Dividing this number by the unobscured aperture area and exposure time yields 16 cts/cm^2/sec. The calibration of 20 ph/ct results in a final measured irradiance at the detector of 320 ph/cm^2/sec. Assuming an atmospheric transmission of 0.8 and 12 inch(300 mm) receiver transmission of 0.9 implies a final irradiance at the aperture of 444 ph/cm^2/sec.

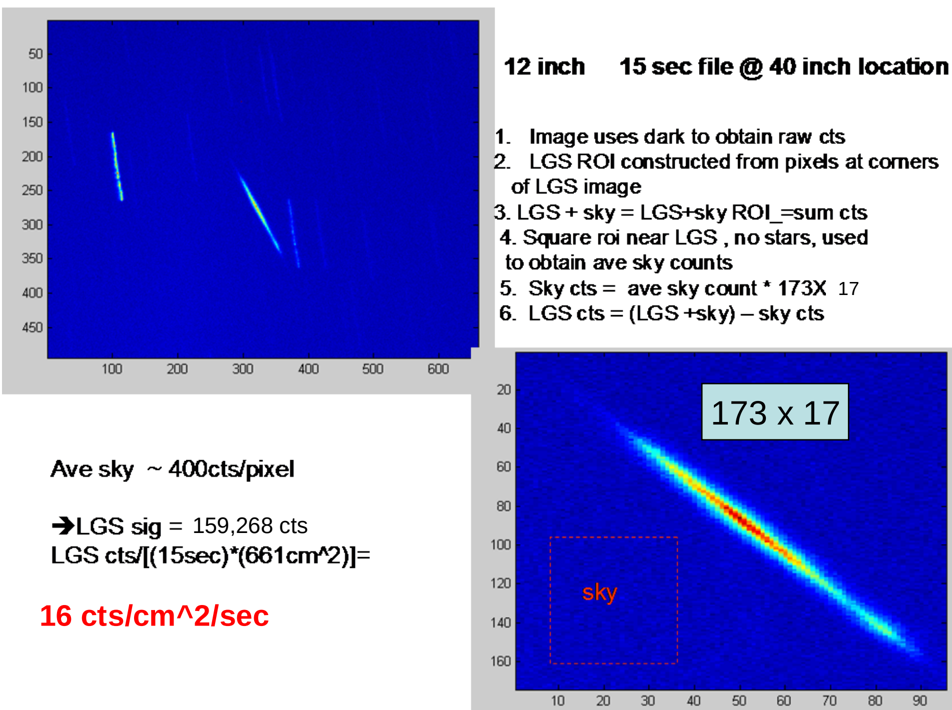

Fig 8 Calculation of measured LGS irradiance using 12 inch telescope sensor

7. Results: Lick irradiance measurement

Lick astronomers gave us data collected during the night of measured counts/ subaperture/frame obtained in the Shack Hartmann wavefront sensor (shwfs) used in their adaptive optics system to correct images of science objects. With the known parameters of 250 hz frame rate, 43 cm subapertures, qe ~ 88% , and 1 e-/ count we were able to calculate the measured irradiance at the aperture from the measured counts obtained. The nominal number used for the calculations below was an average irradiance at the Shack Hartmann wavefront sensor of 400 cts/sub/frame. Using these parameters yields a value of ~ 61.6 ph/cm^2/sec at the sensor. Assuming an atmospheric transmission of 0.8 and telescope transmission of 0.2, we get a final irradiance at the aperture of 385 ph/cm^2/sec.

In order to compare this number to that obtained by our captured images a second calculation was made to convert this number to an equivalent visible magnitude, since this is a convenient number used by the LGS community to compare irradiance levels. Our method to calculate this magnitude from the irradiance will be explained next.

The blackbody star model of equation (1) is solved for the visible magnitude expected from the irradiance in ph/cm^2/sec obtained from the Lick wavefront sensor measurements and our Laser Guide Star images as explained previously. Appropriate parameters for each telescope and detector used : QE, atmospheric transmission, telescope transmission, and filter or detector bandwidth. A simple expression results from this procedure which is given as equation 2

$$D\varphi/dt = 1e6 * 10^{(-.4mv)} \text{ ph/cm}^2\text{/sec} \quad (2)$$

From which the magnitude is determined as,

$$m_v = -2.5 \text{ LOG } [(D\varphi/dt)/ 1e6] \quad (3)$$

In this way, the Lick measurements of the LGS, as well as our irradiance measurements of the LGS using the captured images can be compared in a similar manner as astronomers relate stars or galaxies.

8. Assumptions using photon sum approach

The method used in this analysis treats the photons collected from the Lick wavefront sensor detector as a sum of all photons from the LGS backscattered irradiance as collected by each subaperture. The LGS viewed in the aperture of the 120 inch receiver is closer to a point source, with a measured angular extent of about 2 arcsec (10 urad). The images we collected off axis represent an extended source with a measured extent of ~ .062 -.068 deg (1.1 mrad), as shown in the geometric measurement section above. However, the collection procedure is the same and the use of magnitude is an established procedure to compare star irradiance to galaxy irradiance.
The other important assumption here is that this procedure assumes a uniform irradiance for the LGS image. This does not appear to be the case, as evidenced by the profiles which show two distinct regions, with a hot spot at the higher elevations. A future analysis will consider more carefully these two regions, but for the present report, the assumption of a uniform distribution will be used. This is not an unreasonable approach to use to compare the Lick data with our off axis data. In both cases it is the total photon sum which contributes to the irradiance or magnitude estimation, and should give some intuition to the on axis vs. off axis distribution of photons.

9.0 Summary of Irradiance measurements

Table 4 is a summary of the methods explained above to compare the Lick collection of on axis photons from the LGS in their wave front sensor camera to our telescope and sensor collections at the off axis points of ½ mile and 4.5 miles from the laser transmitter.

Table 4 Irradiance measurements of Lick guide star and resultant calculated visible magnitude

System (tatm=.8)	sensor	exposure time(sec)	measured cts/cm^2/se	cal ph/ct	Irrad at det ph/cm^2/sec	Irrad at tel ph/cm^2/sec	vis mag\ (calc)
Lick 3 meter	e2v CCD-39		54	1.14	61.6	385 (tel=.2)	8.53634818
120mm at 40"	DSI	30	119	3.5	417	580 (tele=.9)	8.09143002
300mm at 40"	Atik16ic	15	16	20	320	444 (tele=.9)	8.38154257
60 mm at Grant Pk	DSI X	180	252	1.5	379	526 (tele = .9)	8.19753564
		120	257	1.5	386	536 (tele = .90	8.19753564

Similar irradiance measurements are obtained from Lick and at the ½ mile and 4.5 mile locations despite having different apertures and sensors at these sites. The magnitude comparisons make this even clearer. Also of note is that the Grant Park measurements using two different exposures yielded almost identical results.

10. Summary of Results

Our results can be summarized as follows

1. The LGS irradiance consisted of two distinct regions from two altitudes
   - the lower altitude had a broad peak with a deep min at a higher altitude
   - at higher altitude the min was followed by a narrow peaked distribution with FWHM ~ 1/3 of the lower altitude distribution
2 .This separation into two distinct distributions was maintained throughout the 6 hours of data collection from 12 midnight until 6 am, with the maximum irradiance shifting from the lower distribution to the higher altitude distribution at ~ 2 am.
3. The LGS measured geometry was ~200m x 14.1 km with an average center height of 92 Km.
4. The measured irradiance at the off axis distances of ½ mile and 4.5 miles is comparable to the on axis Lick measurement although different apertures, focal lengths, and different sensors were used at each location.
5. Blind pointing of an off axis telescope to capture the LGS image has been accomplished using only knowledge of the elevation, azimuth, and location of the laser transmitter and receiver.

11. Acknowledgements

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