Performance Comparison

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This note gives a comparison of the ghost and scattering performance of the proposed Lund Earthshine telescope, and the ”state of the art” Earthshine telescope implemented at Big Bear (Goode) and soon on Tenerife (Pallé). Only scattering from the front surface of the front lens has been included in the analysis, that is all mounts, stops and the “model” cylindrical enclosure of the two telescopes have been assumed 100% absorptive.

Both constructions consist of a refracting doublet followed by an afocal relay providing room for a Lyot stop. Detailed knowledge of all the (commercially available) used lenses makes it possible to compare the two configurations assuming identical lens coatings (WAR: Broad band anti-reflex coating consisting of a quarter-wave layer of MgF_2 and a half-wave layer of La_2F_3). Since contributions to scattering from all mounts and enclosures have been neglected, the performance difference is solely due to the difference in the optical system configurations and the specific lens geometries.

1) The Lund Earthshine Telescope

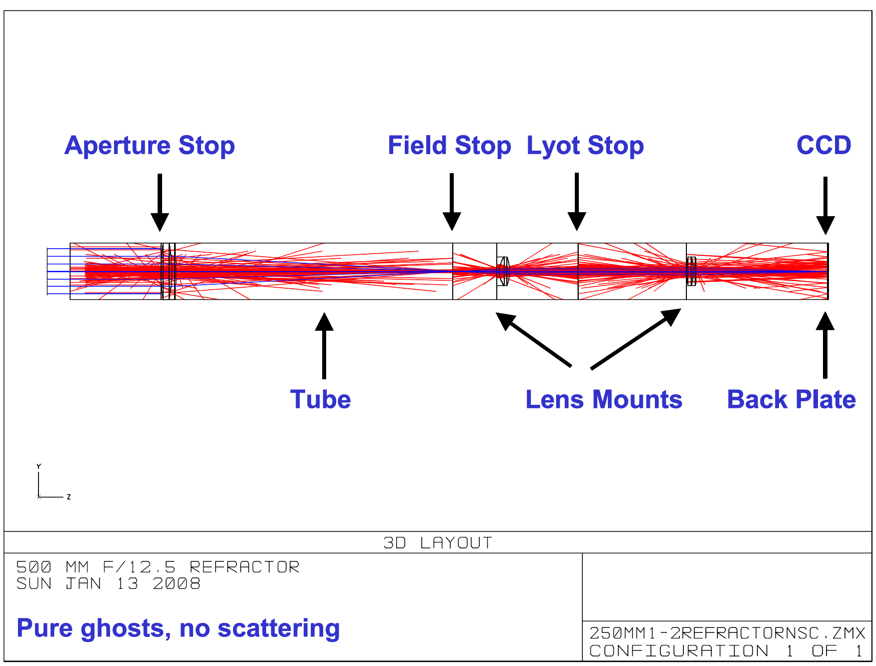

Figure 1: Configuration used for ghost analysis of the Lund telescope. Blue rays belong to a sequential raytrace and red rays belong to a non-sequential raytrace taking Fresnel reflection and refraction into account.

1.1) Ghost performance

The calculations presented in the following were performed using the optical software package Zemax-EE. In order to evaluate the ghost level compared to the peak intensity in total a power of 1 W coming from an axial point at infinity was launched through the entrance pupil. The CCD was modeled as a 512x512 array of 13x13 μm^2 pixels (Andor iKom-M DU-937N-BV), and the central 6x6 pixels collecting the direct image of the axial point were taken out for comparison with the ghost level. The CCD was assumed to have a reflectivity of 5% (QE = 95%).

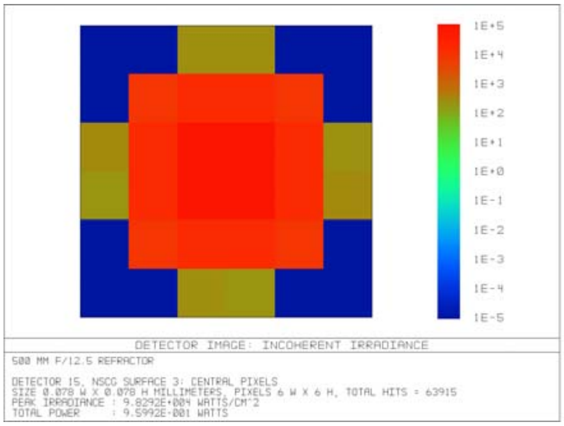

Figure 2: Intensity level in the central 6x6 pixels. 10^5 rays launched towards the aperture stop.

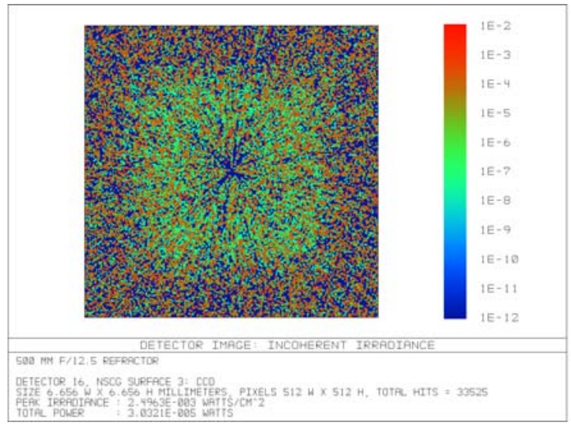

Figure 3: Intensity level over the full CCD (central pixels removed). 10^5 rays launched towards the aperture stop.

Figure 2 shows that the intensity level in the four central pixels is 9.83×10^4 W/cm^2. From Figure 3 we get that in total 3.3×10^{-5} W ghost-power is collected over an area of 0.6656^2 cm^2 resulting in an average ghost intensity level of 6.84×10^{-5} W/cm^2. Hence the signal to noise ratio SNR_g (peak level to the ghost level) is:

$SNR_g = 1.45 \times 10^9$

Figure 3 also shows that a discernable contribution (the square green feature) to the ghost level comes from light bouncing off the CCD and being reflected back towards the CCD by one of the lens surfaces.

Aiming at a precision of 0.1 % (10^{-3}) in the dark side illumination and a ratio of 10^4 of the bright and dark side illumination, the maximum allowed number of brightly illuminated pixels will be $4R/10^7$ = 580. When the Lunar phase changes, the number of brightly illuminated pixels will change, and so will their contribution to the background in the dark pixels. If there are more than 580 bright pixels these variations will surpass the 0.1 % precision level. This seems to indicate that light from the bright side of the Moon must be blocked during dark side exposures unless the background variations from the bright pixels can be calibrated out.

1.2) Scattered light performance

Only the effect of light scattered from the front face of the front lens has been considered in the following. In order to evaluate the effect of this at the detector one must assume a scattering model, which for simplicity has been taken to be Lambertian (other models are possible in Zemax). To put up a model for the scattering signal to noise ratio SNR_{sc} as function of the scatter fraction x (between 0 and 1) three parameters must be known: (i) The central intensity level CI_0 (W/cm^2) in case of no scattering. (ii) The total power TSC_1 (W) scattered to the detector (W) in case of 100% scattering at the front surface. (iii) The width w of the detector. SNR_{sc} is then given by:

$$SNR_{sc} = \frac{CI_0(1-x)w^2}{xTSC_1}$$

Since the total ghost power TGP_0 (W) in case of no scattering is known, the total signal to noise ratio SNR_t from both scattering and ghosts can also be calculated as function of the scatter fraction x from:

$$SNR_t = \frac{CI_0(1-x)w^2}{TGP_0(1-x)+xTSC_1}$$

Figure 4 shows SNR_g (green), SNR_{sc} (red) and SNR_t calculated as function of x for the following parameters:

CI_0 $= 9.77\mathrm{x}10^4$ W/cm^2
TGP_0 $=2.91\mathrm{x}10^{-5}$ W
TSC1 $=3.55\mathrm{x}10^{-5}$ W
w =0.6656 cm

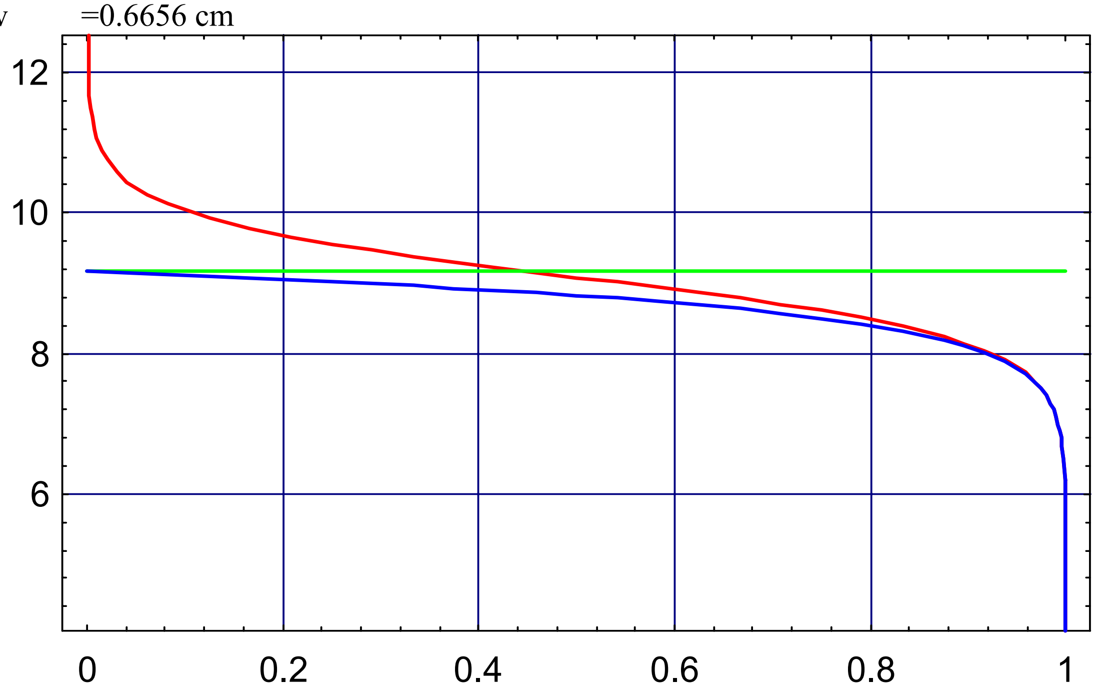

Figure 4: Ghost induced signal to noise ratio (green), scatter induced signal to noise ratio (red) and total signal to noise ratio (blue) as function of the scatter fraction for the Lund Earthshine telescope. Vertical (SNR) axis is logarithmic.

The scatter fraction x_e for which the scattering level is equal to the ghost level is determined by $(1-x_e)TGP_0 = x_e TSC_1$ leading to

$$x_e = \frac{TGP_0}{TGP_0 + TSC_1}$$

which for the Lund telescope turns out as x_e = 45 %. Hence keeping the front surface very clean may not be an important issue for the signal to noise ratio. Scattering does however affect the integration time which is inversely proportional to $(1-x)CI_0$.

2) The Big Bear Earthshine Telescope

In the following similar calculations are presented for the Big Bear Earthshine telescope. The layout is shown below in Figure 5

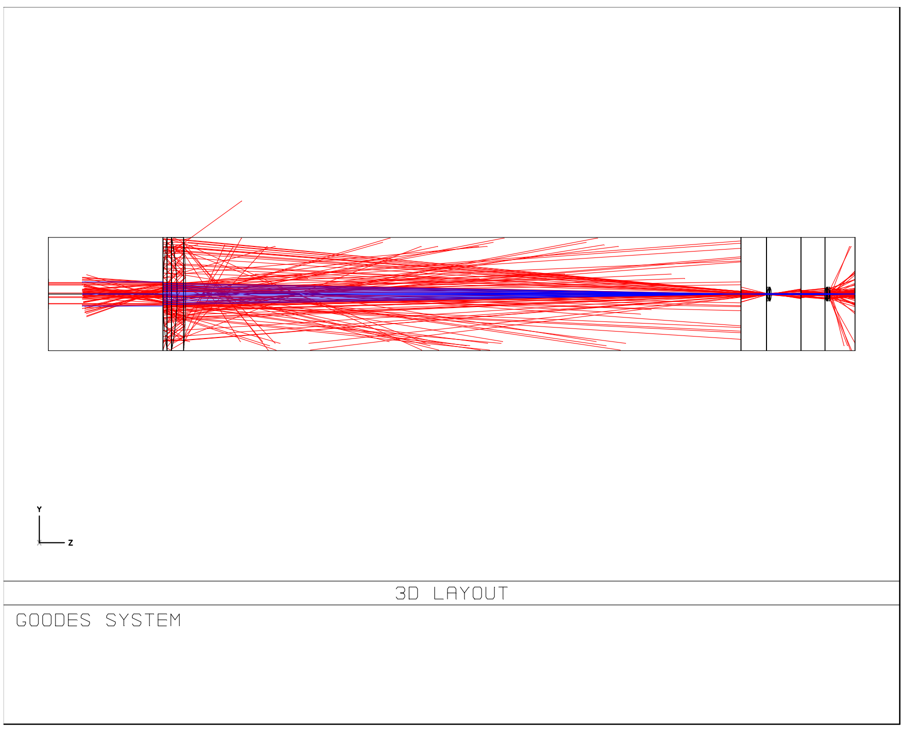

Figure 5: Configuration used for ghost analysis of the Big Bear telescope. Blue rays belong to a sequential raytrace and red rays belong to a non-sequential raytrace taking Fresnel reflection and refraction into account.

2.1) Ghost performance

The analysis was performed in exactly the same way as for the Lund telescope. Results are shown below in Figures 6 and 7.

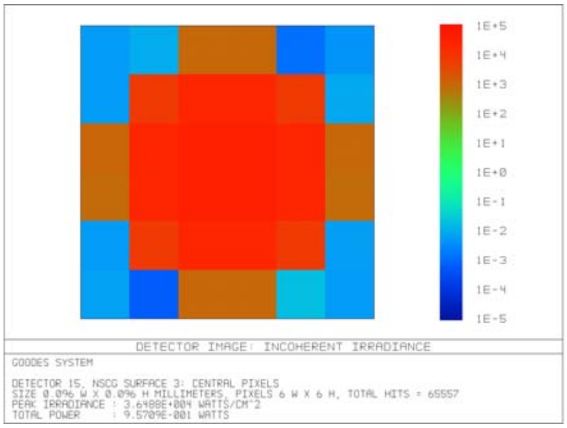

Figure 6: Intensity level in the central 6x6 pixels. 10^5 rays launched towards the aperture stop.

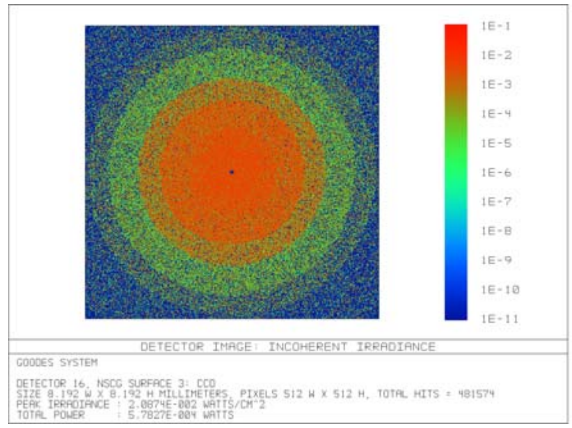

Figure 7: Intensity level over the full CCD (central pixels removed). 10^5 rays launched towards the aperture stop.

Figure 6 shows that the intensity level in the four central pixels is 3.65×10^4 W/cm^2. From Figure 7 we get that in total 5.78×10^{-4} W of ghost-power is collected over an area of 0.8192^2 cm^2 (512x512 pixels of 16x16 μm^2 compatible with the Cascade 512B camera) resulting in an average ghost intensity level of 8.61×10^{-4} W/cm^2. Hence the ratio of the peak level to the ghost level is:

$SNR_g = 4.24 \times 10^7$

Hence the Lund telescope is a factor of 34 more efficient in suppressing the ghost level than is the Big Bear telescope.

Aiming at a precision of 0.1 % (10^{-3}) in the dark side illumination and a ratio of 10^4 of the bright and dark side illumination, the maximum allowed number of brightly illuminated pixels will be $4R/10^7 = 17$. When the Lunar phase changes, the number of brightly illuminated pixels will change, and so will their contribution to the background in the dark pixels. If there are more than 17 bright pixels these variations will surpass the 0.1 % precision level. Hence the Big Bear telescope will certainly need filtering of the bright side when dark side measurements are taken.

2.2) Scattered light performance

The scattered light performance was evaluated in the same way as for the Lund telescope using parameters resulting from a Zemax analysis. Figure 8 shows SNR_g (green), SNR_{sc} (red) and SNR_t calculated as function of x for the following parameters:

CI_0 $= 3.58 \times 10^4$ W/cm^2
TGP_0 $= 5.70 \times 10^{-4}$ W
TSC1 $= 1.65 \times 10^{-5}$ W
w $= 0.8192$ cm

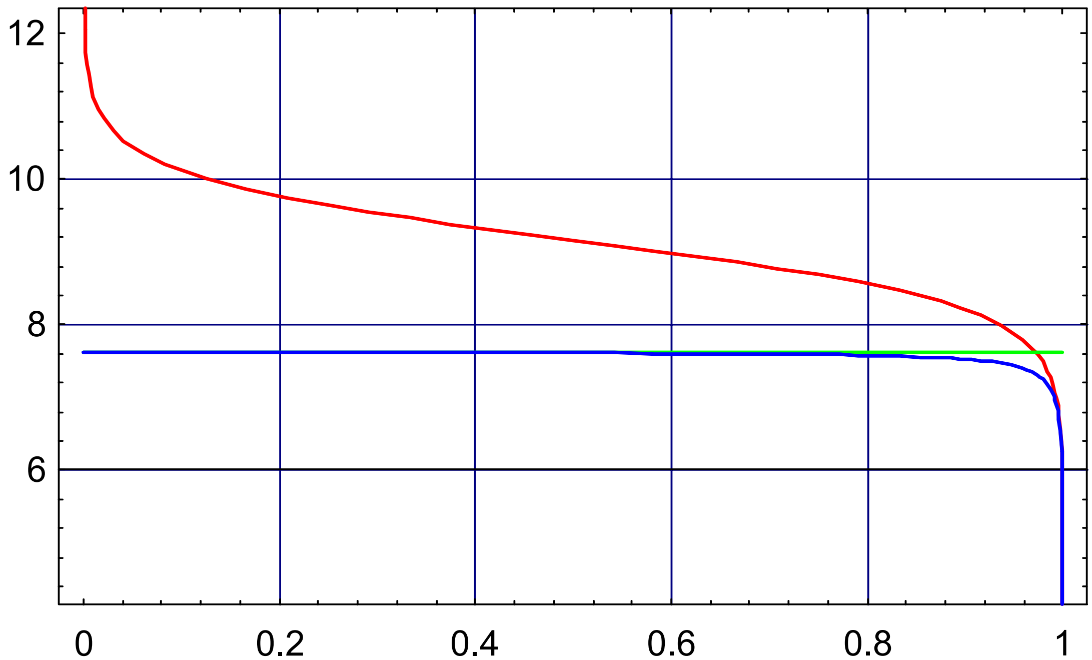

Figure 8: Ghost induced signal to noise ratio (green), scatter induced signal to noise ratio (red) and total signal to noise ratio (blue) as function of the scatter fraction for the Big Bear Earthshine telescope. Vertical axis (SNR) is logarithmic.

The scatter fraction for which the scattering level is equal to the ghost level is x_e = 97%. It should however be kept in mind that scattering at such high levels drastically affects the exposure time. The reason for the high tolerance level for scattering is of course the quite poor ghost performance. This could be improved significantly having lenses with a longer focal length in the 1:1 relay optics of the Big Bear telescope.