A brief report on the optical design of the ROBO-AO LGSF
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1 Introduction

The aim and objective of this design is to develop the necessary optics that would focus a 0.355 nm laser beam at a distance of about 10 kms above the earth's surface. The initial major constraint was to keep the length of the optics to about one meter, but this constraint was later waived away; the second major constraint was to use glasses that would have high transmission in the UV and also to use minimum number of lenses, so that aligning them does not become a major issue; the third major constraint was to keep the exit aperture of the lens to about 150 mm.

A 2D layout of the optical design can be seen in Fig.1. It essentially consists of four lenses; out of which the first lens is a off-the-shelf Melles-Griot bi-concave lens, it diverges the narrow pencil of the laser beam (NA=0.0009) to a diameter of about 160 mm, the second and the third lens collimates the beam and last lens focuses the beam at a distance of 10 kms. All the three large lenses would be made from fused-silica and have a central thickness of 30 mm. The length of the entire optics (from the waist position of the laser to the last lens) is about 3.3 meters.

2 Design version 1.0 (LGS_16_2) (See Twiki)

2.1 Analysis and Results

The optics has a focal length of 54 meter. Fig. 2 shows the spot-size of my design for various field angles and Fig. 3 shows the wavefront map. It can be seen that even for an object height of 3 mm, the geometric spot size radius is only $0.04''$.

The spot radii and their location in the image plane for various field angles in the sky are:

y-Field (in sky)	Size (μm)		Loc. (mm)
	rms	geo	
0	69	367	(0,0)
$7.5''$	69	386	(0,2)
$15''$	72	391	(0,4)

2.2 Lens Parameters

All the lens parameter can be seen in the table below:

Surf	Radius	Thickness	Glass	Dia
OBJ.	Inf.	420		1.033
1	Inf.	1300		1.7
2	-20.9	2	Fsilica	19.1
3	20.9	0		19.1
4	Inf.	900		3.9
5	2891.008	30	Fsilica	165
6	-1610.649	50		168
7	2483.772	30	Fsilica	174
8	-743.41	366		175
9	431.099	30	Fsilica	158
10	336.75	10 km		153

2.3 Laser Parameters

To have about 95% of the laser power at 61 mm of the exit aperture, with a 5% cut-off, we used Apodization factor of 1.5, Numerical aperture value of 0.0011 (1.22*0.0009) and a Gaussian beam.

2.4 Location of the steering mirror

The Steering mirror can be located near the approximate pupil position about 1100 mm away from the laser waist and 200 mm in front of the bi-concave lens. Using a mirror of 10 mm diameter I could evaluate that a tilt of the mirror by 0.0005° (from nominal position) would shift the image position to 4 mm in y direction only (there is no shift in x direction), the image location of an $15''$ field in the sky; (here the mirror stroke was 0.1 μm).

2.5 Focus adjustment between 6 to 12 kms

Good focus can be maintained between 6 - 12 kms simply by adjusting the separation between the last two lenses which is 366 mm for the best focus at 10 km. The table below shows various spot radii (rms and geo. in μm) for different field angles in sky:

			Field				
		0(″)		7.5(″)		15(″)	
Dist(km)	Separation(mm)						
10	366	69	367	69	379	70	371
6	366.764	919	2031	919	2037	919	2050
12	365.809	490	678	490	675	498	683

2.6 Percentage Transmission

2.6.1 Reflection loss

The percentage of light reflected from an interface is

$$r = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 \tag{1}$$

For glass air interface, with 1.48 as the RI of fused silica at 0.355 μm, we have

$$r = \left(\frac{1 - 1.48}{1 + 1.48}\right)^2 = 0.037 \tag{2}$$

That is 96.25% of the light is transmitted per surface; my optics has eight surfaces; hence $(.9625)^8 =$ 74% of the available light incident light is transmitted by the LGSF. AR coating would improve the situation.

2.6.2 Absorption loss

The loss due to absorption per 10 mm for fused silica is about 0.1% at 0.3nm (see Schott, Twiki), so the transmission will be better than 99% (for three lenses) if loss is due to absorption alone.

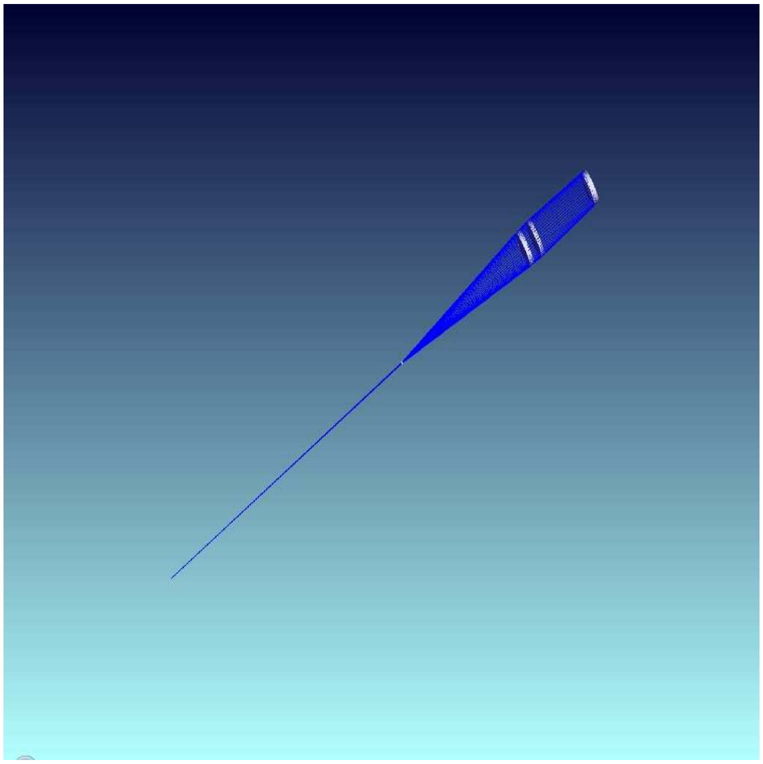


Figure 1: Optics of the ROBO-AO LGSF

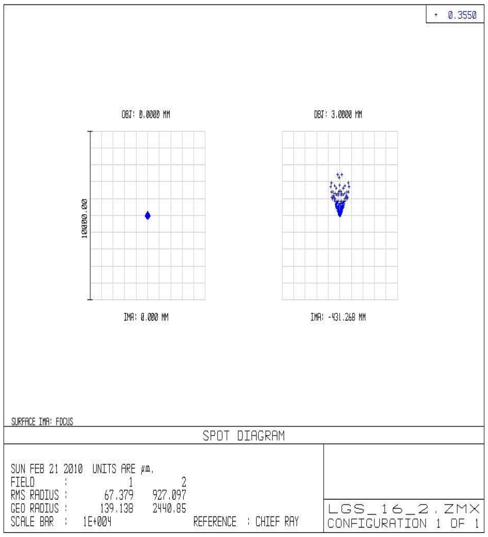


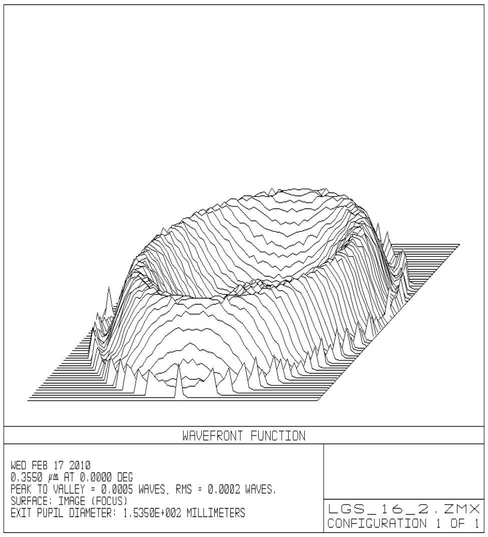
Figure 2: Spot diagram of the ROBO-AO LGSF

3 Acceptability as per the Optical Requirements Criteria

RAO-LGSRD00015: The spot sizes are much less than 0.3″
RAO-LGSRD00016: Acceptable
RAO-LGSRD00017: Although the design is optimised at 10 kms, it works well within the range 6 - 12 kms simply by adjusting the separation between the last two lenses (366) by few mms only
RAO-LGSRD00018: Acceptable
RAO-LGSRD00019: Acceptable
RAO-LGSRD00020: Incorporated in the design
RAO-LGSRD00021: Incorporated in the design
RAO-LGSRD00022: Will be considered in the mechanical design
RAO-LGSRD00023: Will be considered in the mechanical design
RAO-LGSRD00024: Made a first order estimate in the report. RAO-LGSRD00025: A PI tip-tilt mirror can be located at some suitable position
RAO-LGSRD00026: Can be achieved with a steering mirror, which can be mounted in the pupil position before the bi-concave lens
RAO-LGSRD00027: Checked with zemax, can be achieved by adjusting the distance between the last two lenses
RAO-LGSRD00028: Mechanical issue

4 Design version 2.0 (LGS_17) (See Twiki)

The structute of this design is same as LGS_16_2 but its optical length is about 1.5 meter only, much shorter than LGS_16_2. All its lens parameters can be downloaded from the RoboAo twiki site. The optics has a focal length of 40 meter.



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WED FEB 17 2010
0.3550 µm AT 0.0000 DEG
PEAK TO VALLEY = 0.0005 WAVES, RMS = 0.0002 WAVES.
SURFACE: IMAGE (FOCUS)
EXIT PUPIL DIAMETER: 1.5350E+002 MILLIMETERS
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Figure 3: Wavefront map of the ROBO-AO LGSF

4.1 Analysis and Results

The spot radii and their location in the image plane for various field angles in the sky are:

y-Field (in sky)	Size (μm)		Loc. (mm)
	rms	geo	
0	41	84	(0,0)
7.5″	41	92	(0,1.4)
15″	42	101	(0,3)

4.2 Focus adjustment between 6 to 12 kms

Good focus can be maintained between 6 - 12 kms simply by adjusting the separation between the last two lenses which is 366 mm for the best focus at 10 km. The table below shows various spot radii (rms and geo. in μm) for different field angles in sky:

		Field					
		0(″)		7.5(″)		15(″)	
Dist(km)	Separation(mm)						
10	366	41	84	41	92	42	101
6	366.8	730	1136	730	1142	730	1140
12	365.8	369	589	389	538	389	538

4.3 Location of the steering mirror

The Steering mirror can be located near the approximate pupil position about 185 mm away from the laser waist and 25 mm in front of the bi-concave lens. Using a mirror of 10 mm diameter I could evaluate that a tilt of the mirror by 0.001° (from nominal position) would shift the image position to 3 mm in y direction only (there is no shift in x direction), the image location of an $15''$ field in the sky; (here the mirror stroke was 0.1 μm).

5 Design version 3.0 (LGS_18) (See Twiki)

This design has a small positive lens as the first lens and two more larger lenses; its concept is similar to the MMT design. Here the positive lens makes a focussed image of the laser aperture first as an f/7 beam, which could be a source of concern.

6 Comparision of the three versions

- Version 1 and 2 has a negative lens as the first lens and so does not have an exact pupil position to place the tip-tilt mirror; since our sky-field requirement is small ($15''$), we probably can get away with the approximate pupil position; we also checked that the tilt in the mirrors produce shift of the image positions in one direction only, the other direction is not effected at all.

  But when we marked the mirror as the stop and applied some off-axis field, we found that chances of vignetting (the 0 degree field and other off-axis points pass through different locations from the last lens) was high. However, it was also noticed that by decentering the first negative lens by 0.2 mm the image location at 10 kms can be shifted substantially. Thus by simply decentering the first negative lens we can change the direction of the beam in the sky; the tip-tilt/steering mirror can be used to control only the jitter in the laser beam due to telescope vibration and not the beam direction.

  This design thus requires two different degrees of freedom (1) the first negative lens to be mounted on a X-Y stage, to control beam directon (2) the tip-tilt/steering mirror to control jitter in the laser beam due to telescope vibration.

- Version 3 uses a positive lens as the first lens and so has a well defined pupil position before it, but it has an f/7 beam after the first lens, which could lead to air blooming. Air blooms at an incident power density of about 10^{11} Watt/cm^2 (Japan J. Appl. Phys. Vol. 14 (1975) No.9; Kyoshi Kato) or at an energy density of 10^6 Joule/cc, (http://en.wikipedia.org/wiki/Directed-energy_weapon).

  Our calculations show that for the MMT laser and the Robo-Ao laser, the power densities are 3×10^{15} Watt/cm^2 and 6×10^{15} Watt/cm^2...so there are large chances that air-blooming can occur. *No one noticed it at MMT ???? surprising!!!*

  One way to check this is to shine Robo-Ao laser on a off-the-shelf lens of same f/# as the first positive lens and check if air blooming occurs!!!! If things work out fine, then we will go by design version 3 and keep versions 2 as stand-by.

NOTE: To incorporate the field angles of the sky to the laser system, the focal length of the optical system was multiplied by tangent of the sky field angle; this gives the image location. This image location was obtained by an appropriate field angle in the laser system.