GBT MEMO 146

Optical Ray Trace Computations For The Laser Ranging System Detector Lens

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Abstract

Analytical and numerical ray trace computations were made of cardinal points, focal properties and spherical aberration for three candidate detector lens arrangements for the GBT Laser Ranging System.

1. Selecting A Lens For The Laser Ranging System

The ranging system for the Green Bank Telescope employs several laser scanning assemblies. Each sends a modulated infrared signal to a distant retro-reflector, collects the back-reflected radiation, and focuses it on a photodetector which is the first electronic element of a receiver. The receiver demodulates the signal and performs a phase comparison measurement to measure propagation delay and, thereby, distance to the optical center of the distant reflector. The detector bandwidth extends to the gigahertz frequency range. The diode photosurface area is then small, to allow this large bandwidth.

The laser beam travels along a path whose round-trip length is typically forty to two hundred and fifty meters. The beam expands, from an initial Gaussian waist diameter of 2.5mm, to 40mm diameter at 100 meters distance and to 80mm at 200 meters. The return beam from the distant retro-reflector is expected to have a waist diameter of about 80 millimeters. The return beam must be focused onto the receiver diode's photosurface, a square area 0.5mm × 0.5mm.

The distance from detector lens to the receiver photosurface is fixed. Signals from reflectors 20 to 125 meters distant must focus on the photosurface area. If one takes into account the properties of gaussian laser beam propagation, the infrared return signal incident on the detector lens may be regarded as coming from an object at a distance approximately twice the distance from the laser to the distant reflector, decreased by the characteristic Rayleigh distance of the laser beam. Near mid-path, the beam aperture is stopped by the aperture of the reflector target. The beam landing spot size on the detector chip should be insensitive to retro-target distance, and fill the chip without excessive spillover. A converging lens or lens pair with 80mm aperture and focal length in the range from 15 to 30 cm would seem appropriate. Commercially available lenses were found which appeared to have potential for good focal spot quality for all target reflector distances. Extensive experimental investigations were carried out by D.Parker on one of these lenses, manufactured by Melles-Griot.

1.1. Computation Of Lens Focal Properties

The lenses to be analyzed are achromat doublets having two external surfaces and a common internal surface. The radii, vertex thicknesses and glass types were provided by the lens' manufacturers. The glasses are standard Schott types, whose dispersion curves are available in the Schott catalog. The glass index of refraction, phase velocity and group velocity of propagation may be calculated at 780nm wavelength from the appropriate dispersion curve. The paraxial effective focal length, back focal length and principal planes may be calculated by commercial ray tracing codes once the indexes and geometric parameters of the lenses are known.

We summarize the physical data of the candidate lenses below: These lenses are cemented doublets.

Lens Type:	Melles-Griot 01 LA0 267	Spindler & Hoyer 322267
Nominal focal length (mm)	300.7	160.1
Aperture (mm)	80	80
R1 (mm)	197.870	104.410
R2 (mm)	−133.700	−81.116
R3 (mm)	−509.460	−365.170
Glass S1-S2	$SK11$	$SK2$
Glass S2-S3	$SF5$	$SF10$
Vertex width (mm) S1-S2	12.5	22.0
Vertex width(mm) S2-S3	7.1	7.0

The dispersion relation for computation of refractive index squared is:

$$\eta^2 - 1 = \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3}$$

The dispersion constants, and computed refractive indexes for the lens glasses at $\lambda = 0.78\mu$m are:

Glass Type:	$SK11$	$SF5$	$SK2$	$SF10$
$B1 =$	1.17963631	1.46141885	1.2818902	1.61625977
$C1 =$	0.00680282081	0.0111826126	0.0072719164	0.01275345
$B2 =$	0.229817295	0.247713019	0.257738258	0.259229334
$C2 =$	0.0219737205	0.0508594669	0.0213823527	0.0581983954
$B3 =$	0.935789652	0.949995832	0.968186040	1.07762317
$C3 =$	101.513232	112.041888	110.377773	116.60768
η	1.55748578	1.65948973	1.599736745	1.712268494

Ray tracing computations for each doublet were made using the Beam3 code (Stellar Software, Berkeley CA). Transverse spherical aberration was examined by tracing the landing height of axis-parallel rays, and rays originating from an axial object point at a distance from 30 meters to 200 meters , on the paraxial focal and image planes . The laser ranging detector lies on the optical axis of the detector lens, and the return radiation is retro-reflected to return on axis. Spherical aberration is the only aberration of importance, since off-axis rays do not reach the detector. Ray landing heights and incidence angles on the paraxial focal and image planes were computed. Optical path lengths from axial object points to the paraxial image plane were also computed.

Ray tracings were also made for a quadruplet configuration of two Melles-Griot lenses, separated by a vertex-to-vertex distance of 0.450" (11.43mm). This lens pair configuration was studied experimentally by Parker and Shelton, to see if a shorter focus configuration would provide better results over the range of retro target distances to be encountered.[D.H. Parker and J.W. Shelton, GBT Document Archive L0070, February 27,1995]. Ray tracing was done for the Spindler & Hoyer lens, which has a focal length near that of the Melles-Griot pair, to see if smaller spherical aberration and smaller focal spot size might be achieved with a single lens.

1.2. Ray Tracing Computations

To use the Beam3 ray tracing code one prepares two files, a system file [FILENAME].OPT which describes the positions of the optical elements in the optical system to be traced, and a ray file [FILENAME].RAY which describes the starting point and initial direction cosines of the rays to be traced, and requests ray output data, ray landing heights and direction cosines at specific optical surfaces. The ray traces were made at a wavelength $\lambda = 0.78\mu\text{m}$.

The optical system file contains the list of surfaces, index of refraction before ray entry into each surface, surface curvature, type of interface (lens, mirror, or aperture), and aperture diameter. A surface may be either a real physical surface or a mathematical refrence surface.

The code output gives the landing coordinates and direction cosines of each ray, at each of the system's surfaces, and the total optical path from the ray's point of origin to its intercept on the last surface of the system. Plots of ray intercepts or direction cosines at any surface are available, versus the ray coordinates or direction cosines at other surfaces.

The axial location of the second focal point and second principal point of a multiplet lens are established by tracing a sagittal ray which enters the lens parallel to its optical axis, at 0.5mm from the axis. The ray trace code provides the ray landing height and slope of the ray to the optical axis at the nominal focal plane of the lens, after refraction through the lens. The output ray can then be computed and also the axial coordinates of its intersections with the optic axis and with the forward extension of the entry ray at, respectively, the second focal point and second principal point of the lens. The effective focal length is $f_{eff} = Z(F2) - Z(H'')$.

Axial coordinates of the first focal point and first principal point of the lens are found by tracing an axis-parallel ray, 0.5mm from the axis, backward through the lens.

The front and back focal lengths of the lens are the distances, respectively, from the first focal point to the first vertex and from the last vertex to the second focal point of the lens. That is,

$$f_{front} = Z(A_1) - Z(F1) \qquad \text{and} \qquad f_{back} = Z(F2) - Z(A_{last}) \ .$$

1.3. Results Of The Ray Tracing Computations

Forward and backward ray tracing of the candidate lenses, at $\lambda = 0.78\mu$m, gives the following results:

Lens Axial Coordinate (mm):	Melles-Griot 01 LA0 267	Melles-Griot pair, 0.450" separation	Spindler & Hoyer 322267
...	...	...	...
Z(First Vertex)	$Z(A1) \equiv 0.0$	$Z(A1) \equiv 0.0$	$Z(A1) \equiv 0.0$
Z(Last Vertex)	$Z(A3) = 19.6$	$Z(A6) = 50.63$	$Z(A3) = 29.0$
Z(F2)	310.8405	185.3083	173.9501
Z(H")	10.1353	28.7656	13.3857
Z(F1)	−297.7893	−141.1824	−158.0047
Z(H)	2.9161	15.3604	2.5082
...	...	...	...
f_{eff}	300.70548	156.54272	160.56441
f_{back}	291.2408	134.6783	144.9501
f_{front}	297.7893	141.1824	158.0047

The transverse spherical aberration was examined for the image of a distant axial object point at several distances from each of the candidate lenses. Ray landing heights on the paraxial image plane and the paraxial focal plane were computed. The displacement of the paraxial image plane from the paraxial focal plane is computed by using gauss' form of the lens formula:

$$(Z(image) - Z(F2)) \cdot (Z(F1) - Z(object)) = (f_{eff})^2 \ .$$

This provides the location of the paraxial image spot for a distant point source. This is not necessarily the best image spot, which might lie near the circle of least confusion, between the paraxial image and focal planes. We tabulate the paraxial image plane separation from the paraxial focal plane for several image distances, for the three lens configurations.

		$Zimage - Z(F2)$ (mm)	
$Zobject$ (meters)	$Melles - Griot$ 01 LA0 267	$Melles - Griot$ pair separated 0.45"	$Spindler\&Hoyer$ 322267
−30	3.0443	0.8207	0.8639
−40	2.2776	0.6148	0.6471
−50	1.8193	0.4915	0.5173
−60	1.5146	0.4094	0.4308
−80	1.1345	0.3069	0.3229
−100	0.9069	0.2454	0.2582
−120	0.7554	0.2045	0.2151
−150	0.6040	0.1635	0.1721
−180	0.5032	0.1362	0.1434
−200	0.4528	0.1226	0.1290
−220	0.4116	0.1115	0.1173
−250	0.3621	0.0981	0.1032

If a laser scanner illuminates a distant retro-reflector the effective object distance is close to twice the distance between the laser and target, less the Rayleigh range of the laser.

The Rayleigh range is: $z_R = \pi w_o^2/\lambda$, where w_o is the gaussian beam waist radius at the laser. The waist radius is obtained from the far field half-angle of divergence of the laser beam θ_{FF} from the relation $w_o = \lambda/\pi\theta_{FF}$. For the Melles-Griot type LT021MD-A diode laser used in the scanners, the manufacturer specifies $\theta_{FF} = 0.2\text{mr}$, which gives a waist radius $w_o = 1.24\text{mm}$ and Rayleigh range $z_R = 6.2\text{m}$.

For the Green Bank Telescope the detector lens will image at a range of object distances between 40 and 250 meters. The distance of the photodetector from the lens will be set at some image distance corresponding to some mean object distance in this range; the detector is set at a fixed distance from the lens. For the 30 cm focal length lens the image distance from the last lens vertex varies from 0.4 *to* 2.3mm beyond the back focal length of the lens. For either of the 15 cm focal length configurations, the image distance from the last lens vertex varies from 0.1 *to* 0.6mm beyond the back focal length of the lens.

Ray traces were run for transverse spherical aberration at the paraxial focal plane and the paraxial image plane for the three lens configurations at a variety of object distances. Ray trace results for object distances of 30, 35, 40, 100, 200 meter and infinite object distance are included with this note, together with sample ray trace files.

The two 15 cm focal length configurations each show spherical aberration that is nearly independent of object distance, for object distances greater than 40 meters, and the aberration at the paraxial focal and image planes is effectively the same. That is, the quality of the focal spot is insensitive to range and to the precise image plane separation from the focal plane. This suggests that if one of these configurations is selected for the detector lens, a setting of the photodetector surface of 0.3 to 0.4 millimeters beyond the back focal plane should be adequate for all object distances.

[Let us note, however, that the lens to photodetector distance will have to be corrected for insertion of a non-focusing optical element between lens and detector, the circular polarization isolator. The isolator will produce a fixed focal shift of the detector plane away from the lens of $t(\eta-1)/\eta$ where t is the isolator thickness and η is its effective index of refraction.]

The Spindler & Hoyer lens 322267 has an image spot size of 0.4 to 0.5 mm diameter, just slightly smaller than the photodetector area, at all target ranges.

The paired Melles-Griot lenses have an image spot size larger than the detector at all ranges; rays entering the lens pair at distances beyond about 25mm from the optic axis do not land within 0.25mm of the optic axis at the image spot.

The single Melles-Griot lens 01 LA0 267 has a smaller focal spot than the other two configurations. At 200 meter object distance the image spot size is below 0.1 mm diameter at both the paraxial focal and image planes. At minimum object distance, near 40 meters, the image spot is smaller than 0.1 mm diameter at the paraxial image plane but is 0.4 mm diameter at the paraxial focal plane. At the closer ranges the image spot size is sensitive to the location of the photodector surface.

Ray traces were run for the Melles-Griot 01 LA0 267 lens with a 3.25mm thick BK7 glass plate inserted before the focal plane of the lens, in order to simulate the image displacing properties of the circular polarization isolator to be used before the photodetector surface of the laser ranging unit. The ray traces indicate that the effect of the plate is to displace the image; placement of the plate in the optical path does not increase the focal spot diameter.

An inspection of the ray traces suggests the following observations:

1. The use of a pair of 01 LA0 267 lenses to shorten the length of the lens to photodetector space leads to a focal spot size that is larger than the half-millimeter square photodetector surface, at all retro-target ranges. Typically, the portion of the lens surface further than 25mm from the lens optic axis will not focus onto the photosurface. The quality of the focal spot for this lens pair is not sensitive to the precise lens to photosurface distance, and is about the same for all object distances between 40 and 240 meters.

2. The Spindler & Hoyer 322267 lens gives a focal spot just a little smaller than the photodetector surface at all ranges. The focal spot size is about the same at all required target reflector ranges and is not sensitive to the precise lens to photosurface distance. Optically it appears to suggest performance at least as good as the pair of 01 LA0 267 lenses and might be superior. It may be easier to center and mount and saves a half inch of space in the optical path. If one is concerned about the possibility of trapping condensed moisture between lens surfaces, in field operation of the laser scanner, the single lens would not present this potential problem. It would be worthwhile to evaluate this lens as a possible alternative to the lens pair.

3. The single 01 LA0 267 lens has a smaller focal spot than either of the 15 cm focal length alternatives. The spot size is somewhat sensitive to the precise choice of lens to photosurface distance at the closer target ranges.

4. The ray traces do not give any reasons to reject any of the three candidate configurations for use in the laser ranging system scanners.

For supporting drawings and documentation regarding GBT Memo # 146 “Optical Ray Trace Computations for the Laser Ranging System Detector Lens” please see GBT Archives # L0081.