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Design and simulation an optical system for transmitting light into the atmosphere

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ABSTRACT

lidar (Light Detention and Ranging) technology is a performing remote sensing application, able to provide range and time resolved measurements of the backscattered (or re-emitted after a stimulation) light from a target invested by pulsed laser light. In this research, after a brief introducing of the different parts of a LIDAR system, it has been studied to design and optimize a concentrating optical system by means of Matlab software.

Keywords: *Light Detention. remote sensing, Optical designing, Laser receiver, Matlab software*

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INTRODUCTION

From the past years, radar systems have been used in radio frequency ranges for detecting the objects such as airplanes, ships and etc. In 1930, these systems have been used in optical wavelengths for measuring the far way distances. After introducing the laser systems, it has been reliable to measure the far way distances with a fast and easy to use application. In 1963, Ligda who was a pioneer in the LIDAR atmospheric applications, used a Q-switch laser as an optical laser. For a laser beam in a LIDAR system, depending on the optical pass between ray and the object during the measuring time, some changes will appear in the amplitude and the wavelength of the wave. Therefore, the returned ray will contain some information about the object.

In addition, by measuring the needed time for sending and receiving the pulse, it would be possible to determine the distance between the station and the object. The simplest LIDAR system includes of a good laser as the ray transmission source, an optical system for gathering and transferring the reflected rays to the detector, a sensitive detector and a computer processing system. The most important issue for a receiver in the LIDAR system is the effective detection of the low intensity radiation. The desired optical pulses for detection should be placed on a sensitive surface of the detector, which is very small, therefore, designing and installation of an optimized optical system which is capable of aggregation of all light-emitting power with the minimum waste of energy on the sensitive surface of the detector is the most important part of designing a remote-sensing system of the LIDAR. The radiation energy is transmitted in several stages. The first case is the spreading of radiation due to divergence which reduces the power of the ray. The rays are dispersed in all directions after a limited reflection of the object's surface. Laser beam divergence is unavoidable during the passing time of the ray in a medium. The optical beam divergence causes the cross-sectional area at the detector location to be much larger than the detector's sensitive surface. The ray also has another dispersion when passing through the atmosphere, which reduces its power. In Fig. 1, the parameters which influence on the transmitted and reflected energy of the ray have been shown. In the following, it has been briefly described how the different factors affecting the power of beam:

A) Assuming P_0 as the initial output power of the transmitted beam.

B) The power at the ground surface would be MP_0, where M stands for the transmission factor of the atmosphere (A is a number between zero and one).

C) The reflected ray from the ground surface based on the Lambertian surface is $\frac{\psi}{2\pi\rho} MP_0$. Where ρ represents the reflection factor of the ground and ψ represents the angular momentum of the reflected energy.
D) That part of the ray that finally received at the measuring station upon reflection from the ground surface and passing through the atmosphere will be equal to:

$$P_R = \rho \frac{M^2 A}{2\pi R} P_0$$

For example, for an initial output power of 2000 watts, the flow factor of 0.8, the opening of the device is 100 centimeters, the flight speed of 1000 km/h, and the ground reflection value of 0.5, the received power would be 800 Nano watt. Therefore, only a small part of the initial energy will be received at the measuring station.

Stages of an optical designing:

Optical designing is the science of improving an optical system for analysis and measurement of the light to gain a better image from the desired object. The optical system must be free of any geometric errors (aberrations), the main task for an optical designer is to correct and control the aberrations. The optical design consists of five main stages:

1-Defining system specifications

The first step in optical designing is to determine the characteristics specifications of the system which depend on the user's requirements. These specifications include the wavelength, focal length, needed performance, accuracy of the measurement, environmental constraints and so on.

2-Selecting an initial design to start:

The next step is to select a design that has the potential to match the desired specification. Proper configuring of the system is the key for reaching to a successful design. The system configuration includes the shape of the lenses, the number of elements and the distribution of the optical power inside the system.

3-Optimization

In designing, the proper adjustment of the variables, constrains and merit functions are essential for optimization. Variables include parameters such as radius, thickness, air gap, refractive index, and nonlinear coefficients. The surface radius is the most effective parameter for correcting the aberrations. The thickness and space of the air gap are less sensitive to the aberrations. The following techniques are used as the standard applications for optimizing the system: changing the curves, thickness, air distances, increase or decrease the variables, changing the effective weight of the different wave fields and wavelengths, identification and correction of the aberrations, increasing or decreasing the refractive rate of the materials, modifying the merit functions to eliminate the aberrations with increasing or decreasing the effective weight or adding new constrains.

4- Evaluating the performance

To evaluate the performance of the optical systems, depending on the requirements, various diagrams are being considered that include the spatial diagram, the encircled energy (ENC) and the modulation transfer function (MTF).

5-Tolerance analysis.

Considering that the optimization result may lead to finding some dimensions for the different optical objects that are not exactly equal to their real physical sample in the market, optical component manufacturers always consider a tolerance value for the dimensions of the objects being under production. This amount of tolerance should be reconsidered in the designing phase so that the result be known before producing the system.

Optical analysis system tools in ZEMAX

1-**Spot diagram**

Spot diagram represents the distribution of the rays from a pointed object in the image space. Two types of the radial parameters can be extracted from the grid diagram displayed in the ZEMAX software. The first parameter is the geometric radius of the spot. This parameter represents the radius of the spherical circle relative to a reference (The main beam, the center of the beam, or the center of the cluster), which includes all the beams generated by a pointed object in the object space, which is comprised in the image plane. The second parameter represents the root mean square (RMS) radius of the of the spot in the object space. To obtain this parameter, the radial distance of each ray from a desired reference point is calculated, and then RMS of all the rays being calculated. The difference between the first and the second parameter is that in the first parameter we have information about the radical distance from the furthest ray from the reference only. But the second is the diameter of a circle, which includes 68% of the total energy of the image. Therefore, in optical designing of the system, it must be smaller than the diameter of the detector's surface.

2-ENC graph

In this graph, the enclosed energy is plotted as a function of the distance from a desired center point. This graph is a good benchmark for evaluating the quality of a design in imaging systems and optical receivers. Because by using this graph can determine the radius of a circle that contains 80% of the energy generated by a pointed object. During the optimization process, in this diagram the radius of the circle which contains 80% of the energy, should be less than the size of the radius in the detector's sensitivity screen.

3-Modulation Transfer Functions diagram (MTF)

The MTF diagram can be considered as one of the most important analysis diagram for imaging systems such as cameras, telescopes, and so on. The MTF function can be considered as the ratio of the output signal to the input signal of the optical system, which is a function of spatial frequency. This diagram shows the modulus of the image relative to the object's modulus, in terms of the function of the space frequency defined for the tangential and vertical response of field angles. It is drawn up. The modulus of an object or image is defined as follows:

$$Modulation = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$

Where I_{max} and I_{min}, respectively indicate the maximum and minimum intensity of the light in the image or object space. The modulation transfer function for an optical transmitter for a specific frequency (ν) is defined as follows:

$$MTF(\nu) = \frac{M_i}{M_o}$$

Where M_i represents the modulus of the object and M_o represents the image modulus. This diagram has a diffraction limit, in which if the desired imaging system is ideal and free of any aberration, its MTF graph is comfort with the diffraction limit. But due to the various aberrations, the MTF diagram is always lower than the diffraction. Therefore, at designing time the aberrations should be reduced as much as possible.

Designing and optimizing an optical system

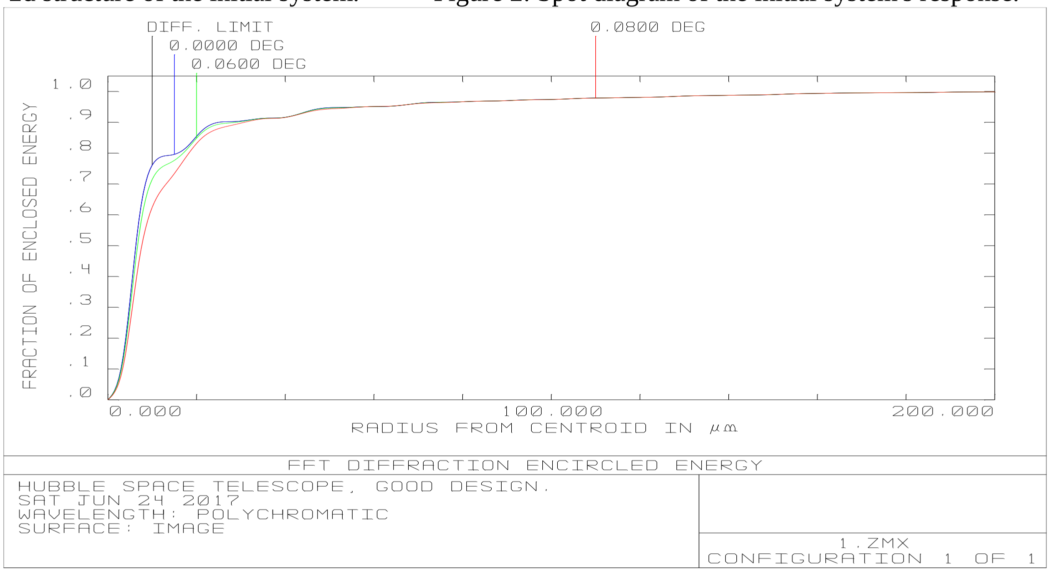
Step 1: Defining an initial system; at first step, by considering the general condition of the LIDAR system and the environmental factors, and based on the basic principles of the optical knowledge, an initial system has been defined in ZEMAX software in the table 1:

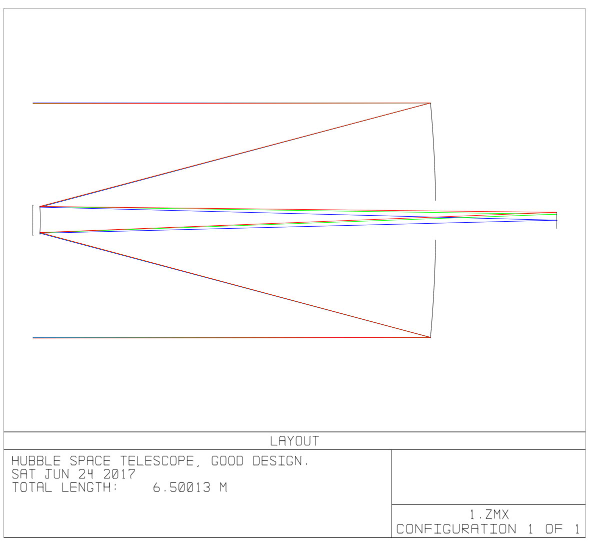
Table 1: Defining the initial system specifications

Surfe:type		Radius		Thickness		Glass		Semi-diameter		Conic
OBJ	Standard	Infinity		Infinity				Infinity		0.00000
1	Standard	Infinity		5.00000				0.155000	U	0.00000
STO	Standard	- 11.040000		-4.906071		Mirror		1.200091		-1.002299
3	Standard	-1358000		6.406200	M	Mirror		0.140559		-1.496860
IMA	Standard	0.631079	V	-				0.080379		0.00000

Based on the specifications above and by choosing other important parameters such as wavelength, wave fields and aperture value, the initial system and the analytic graphs and tables are ready to check. The 2d structure of the system and the corresponding spot diagram and MTE graph have been shown as below.

Figure 1: 2d structure of the initial system. Figure 2: Spot diagram of the initial system's response.





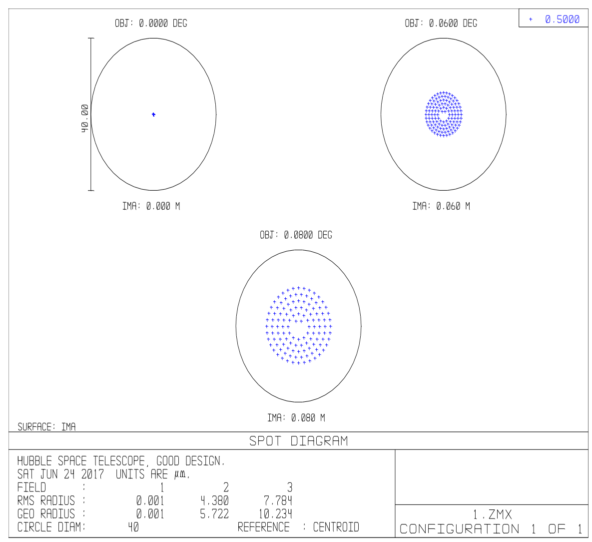


Figure 3: The corresponding MTF graph of the initial system.

As we can see in the analytic graphs of the initial system in figure 2 and figure 3, all the gathered information shows the perfect and acceptable performance of the system, but in practice this system cannot be used for LIDAR purposes because of the small size of the optical system which is only about 6.5 mm (Figure 1). Therefor the size should be increased by a reasonable rate so that it would be suitable for the desired purposes. For achieving this goal, the optical specifications have been changed as the table below to form the second system:

Table 2: Optical specifications of the second system.

Surfe:type		Radius		Thickness		Glass		Semi-diameter		Conic
OBJ	Standard	Infinity		Infinity				Infinity		0.00000
STO	Standard	Infinity		100.00000				30.000000	U	0.00000
2	Standard	-171.00000		-37.00000		Mirror		30.000000	U	0.00000
3	Standard	-351.00000		66.260822		Mirror		17.000000	U	0.00000
IMA	Standard	Infinity		-				1.00000	U	0.00000

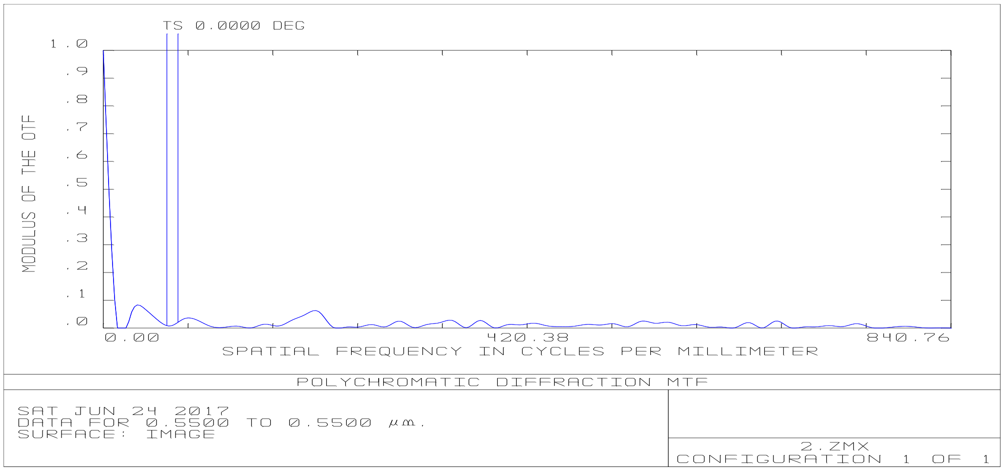


Figure 4: Spot diagram of the second system. The total length has been assumed to be 150 mm. and the spot diameter is 57.7 µm. In comparison with the former system, we can see that this parameter has been increased so we can expect that the other analytic graphs show the decrease in the system performance.

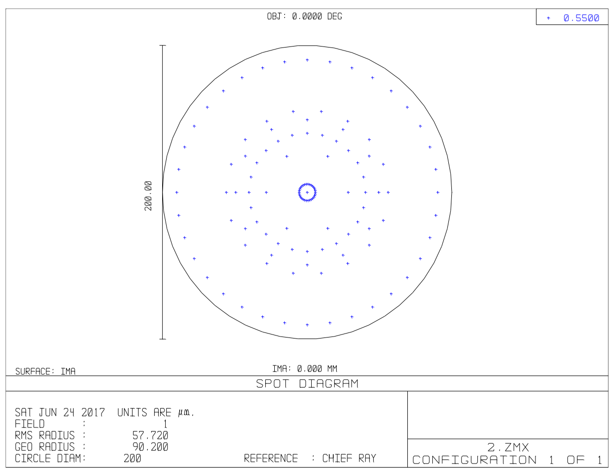


Figure 5: MTF graph of the second optical system. As it is clear in the graph, the performance of the system has been decreased for almost all frequencies.

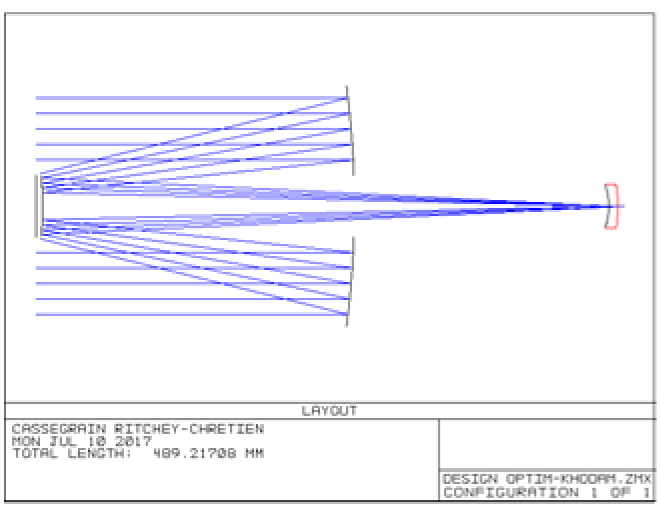


Figure 6: 2d scheme of the final design which includes a lens near to the image's surface for more focusing of the rays.

As we can see from the spot diagram and MTF graph in figure 5, although the new system has an acceptable size but the final corresponding results are not suitable enough to be a good optical system for LIDAR purposes. It's noticeable to say that all the optimization processes have been done for this system but because of bad choosing the parameters and conditions, the final result from the optimization still is far from the desired goal. Therefore, it needs to change the optical design, so for having more conservative rays at the image's surface, a lens being used as below table:

Table 3: Optical specification of the final system.

Surfe:type		Radius		Thickness		Glass		Semi-diameter		Conic
OBJ	Standard	Infinity		Infinity				0.000000		0.00000
1	Standard	Infinity		265.00000				26.000000	U	0.00000
STO	Standard	-138.00000		-260.00000		Mirror		100.000000	U	-1.046192
3	Standard	-216.00000		471.717084		Mirror		25.000000	U	-2.915001
4	Standard	35.000000		5.000000		SF11		18.000000	U	0.00000
5	Standard	50.000000		5.000000				18.000000	U	0.00000
IMA	Standard	Infinity		-				1.328602E-004		0.00000

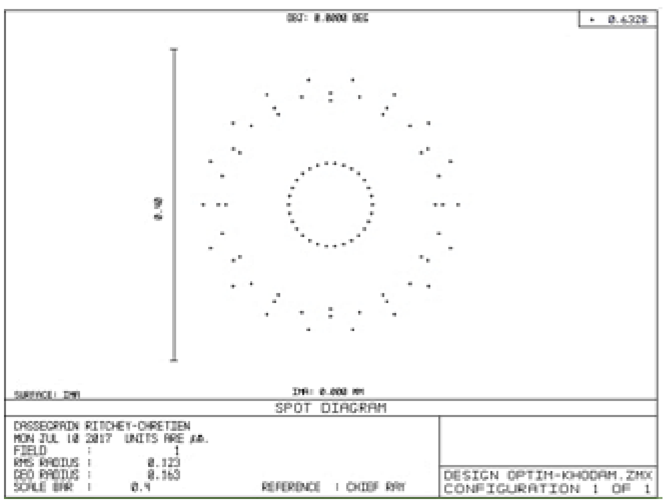


Figure 7: Spot diagram of the final design. The corresponding RMS diameter of the spot is just 0.123 µm. So this new system could gather and focus the most reflected energy from the earth's surface.

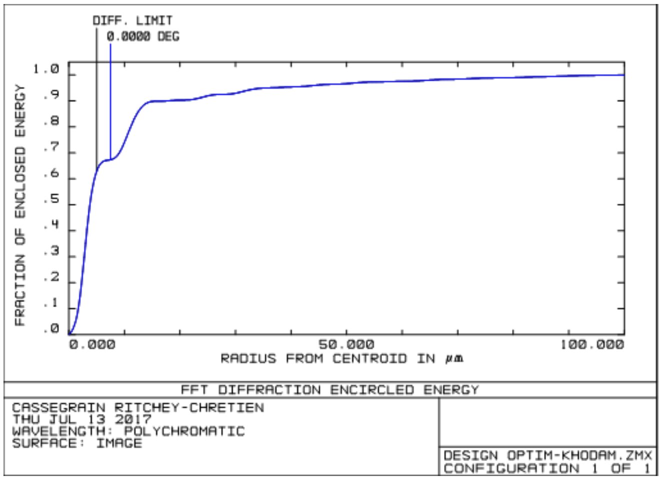


Figure 8: ENC graph of the final design. The good performance of the system is obvious and the fraction of the enclosed energy is conformed with diffraction limit.

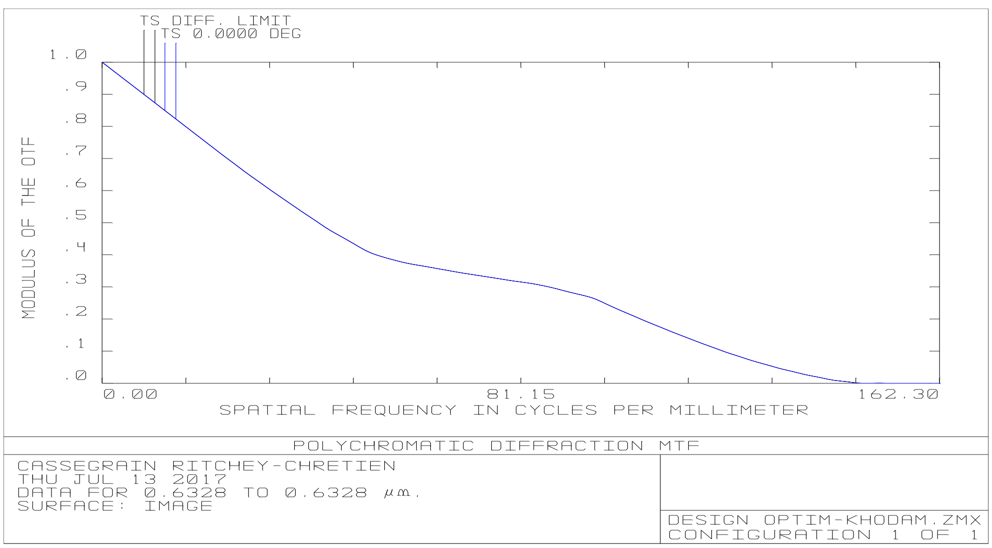


Figure 9: MTF graph of the final design.

Based on the results in figures 7 to 9 we can see that by choosing the good parameters and conditions and performing the optimization process, almost the best consequents has been obtained, but still one issue must be considered, and that is the errors related to making the real size elements for practical purposes. Therefor the next step, tolerating must be performed

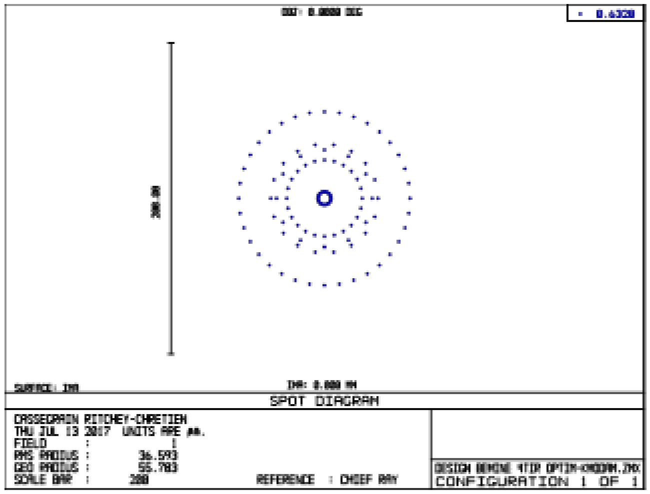


Figure 10: Spot diagram of the modified final system based on the tolerance analysis. The RMS diameter of the spot is about 36.6 µm which is an acceptable value for the most purposes.

Tolerance analysis:

One of the most important parts of an optical designing is tolerances analysis which lead to make better sense of the system performance in real situation. In other word it needs to consider what the manufacturer has said to take into account and evaluate the system performance by applying the errors which are mainly related to the precision of the lenses manufacturing process. These errors sometimes are so great that the image quality is drastically reduced, the optical design needs to be desired. After the application of these tolerances, the increase in this quantity is investigated.

Table 4: Optical specification of the modified final system based on the tolerance analysis

Surfe:type		Radius		Thickness		Glass		Semi-diameter		Conic
OBJ	Standard	Infinity		Infinity				0.000000		0.00000
1	Standard	Infinity		265.000000				26.000000	U	0.00000
STO	Standard	-700.00000		-240.000000		Mirror		100.000000	U	-1.046192
3	Standard	-300.00000		405.000000		Mirror		30.000000	U	-2.915001
4	Standard	50.000000		7.5000000		SF11		18.000000	U	0.00000
5	Standard	-120.000000		5.968061				18.000000	U	0.00000
IMA	Standard	Infinity		-				1.0000000	U	0.00000

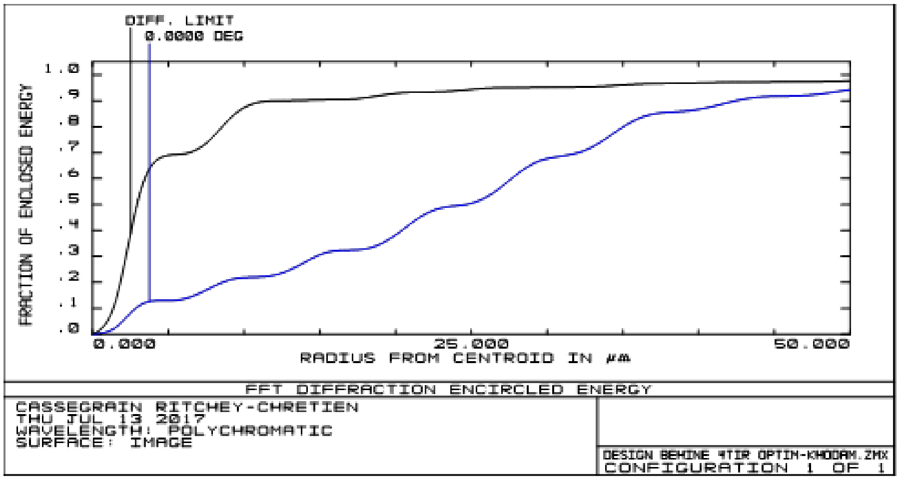


Figure 11: ENC graph of the modified final system. The good performance of the modified final system is also obvious in the MTF and ENC graphs in Figures 11 and 12 which show that in most cases, the system has been kept its good response to the reflected energy from the surface.

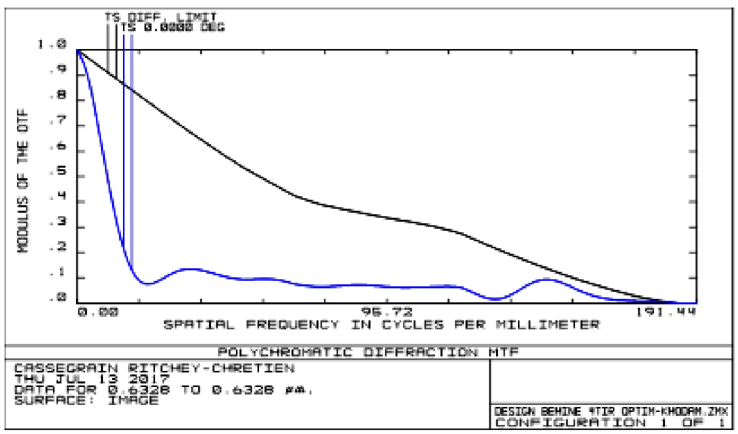


Figure 12: MTF graph of the modified final system which shows the good performance of the system in transferring the contrast from object space into the image space.

Conclusion

In this study we introduce a brief history of the LIDAR application in different conditions. Because of the poor energy of the reflected rays from the surface in many application, the needs of designing and making a high performance and applicable optical system for gathering the most received energy is important. For this reason, in this study we use ZEMAX software to design an initial optical system with focusing on LIDAR application and the mentioned system got promoted many times by means of optimization tools in the software and also from using the trust condition for approaching to a strong and reliable optical system which can rely on its good performance even after tolerance analytics.

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