

Simulation and Evaluation of a Variable Effective Focal Length of Refractive Binocular Telescope

Alaa K. Shwayyea

Department of Physics, College of
Education for Pure Science \ Ibn Al-Haitham, University
of Baghdad, Baghdad, Iraq.
alaa.b.h@ihcoedu.uobaghdad.edu.iq

Alaa B. Hasan

Department of Physics, College of
Education for Pure Science \ Ibn Al-Haitham,
University of Baghdad, Baghdad, Iraq.
alaajizany@yahoo.com

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Abstract

The telescope works to magnify images of distant objects in general, but it needs special optical elements to complete the task to the fullest. The telescope needs optimal balance values of the optical parameters used to produce the best image, such as the effective focal length and the diameter of the pupil aperture, which are combined in a single concept called the focal number. The ground-based binary telescope relies on special lenses and an exceptional prism to achieve a hybrid design that produces clear images of relatively distant terrestrial objects. The pupil diameter of the telescope is relatively large to ensure that the largest possible amount of light is received, and as a result, a good image is obtained.

In this work, an achromatic objective lens and a Porro prism has been used to reduce the length of the telescope and change the path of the rays to the eyepiece, in addition to the presence of a flat convex lens behind the prism to collect the rays coming from it to reach the eyepiece. The effective focal length of the optical system was changed to illustrate the effect of this factor on the performance of a telescope and as a result of its effect on the image quality.

Keywords: binocular telescope, zemax program, effective focal length, modulation transfer function

1. Introduction

The optical design software has a major role in developing designs and their diversity in various fields scientific and engineering design software saves effort and time when used, and take advantage of this Programming by engineers and workers to communicate their idea in a clear and easily visualized manner, and absorb them to establish a project optical design is one

of the most important steps. That it precedes the manufacture of optical systems to obtain the appropriate specifications in terms of parameters and specific design constraints called performance requirements (parameters) depending on the surrounding conditions (tolerance) [1]. The choice of design materials is one of the important factors in the success of any design, and this is taken into account The material cost and taking into account the availability and quality of materials to obtain the design with high efficiency and appropriate cost [2, 3].

The designer needs to know all the details of the optical design; the main purpose of the design, the type of materials that are used, the size of the telescope and its field of use, all these things are necessary to give an idea to the designer about the features of the design and the appropriate program [4, 5].

In this work, Zemax program was used for optical designs with mixed ray tracing mode (sequential and non-sequential) due to the design need for this type of mode. Zemax program is characterized by a huge dynamism that qualifies it to give an accurate design for the binocular telescope. The program also provides a set of analysis tools to give an appropriate assessment of the quality of the image and thus judge the performance of the design [6].

The most important analysis tools used in the Zemax program are the point spread function PSF, spot diagram, optical transfer function OTF, ray fan aberration and optical path difference OPD. All of these tools give an idea of the image quality by measuring the amount of aberration in the image, the distribution of ray propagation in the image plane, in addition to the amount of radiant energy reaching the image surface, which gives an idea of the contrast and resolution of the image [7, 8].

2. Optical Design

The purpose of optical design is to design an optical model compatible with the purpose for which it was designed its term, taking into account the industrial cost as it is one of the important economic factors, in addition to other matters related to durability and industrial quality. Various designs are evaluated using techniques Modern computers consist of a variety of software specially prepared for this purpose [9]. This software has dynamics High in designing any model with accuracy and high quality according to the pre-established conditions, such as the design of the microscope camera, camera lenses, telescope, and microscope and solar centers (solar cells) and various solar systems such as solar cells detectors solar concentrators [10].

The characteristics of the telescope are determined by several optical parameters. These parameters are the effective focal length, the diameter of the pupil aperture of the objective lens, and the type of glass used to manufacture the lenses and prisms. The effective focal length is determined by calculating the focal length of each lens used and the length of the optical path traveled by the light inside the telescope. The amount of effective focal length varies according to the type of design, the number of curvature radii of the lenses used and the refractive index of the lenses and the medium surrounding the lenses [11].

Telescope focal length is a distance from the objective lens to where it focuses collimated light. That is when the light arrives from an object far enough that the wavefront entering the objective lens is practically flat, and the light rays are practically parallel. In a complex objective lens, the effective focal length is determined by the focus separation (s) from the last surface and the height of the marginal ray (h_m) on it, as shown in **Figure (1)**. The effective focal length is represented in the equation [12]:

$$f = \frac{sD}{2h_m} \quad (1)$$

Where D is the aperture diameter of the objective lens.

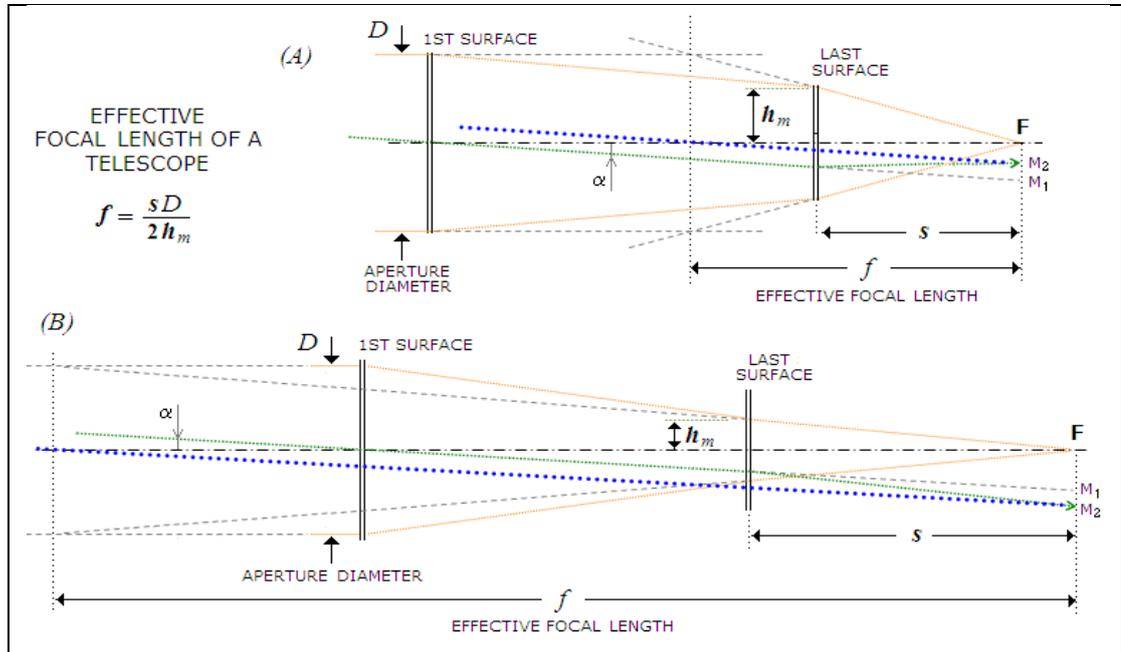


Figure 1. The effective focal length of a binocular telescope [12]

3. Internal Components of Binocular Telescope

The internal components of the binocular telescope include a set of optical elements defined by a set of parameters included in the lens data editor LDE in zemax program. LDE contains rows and columns, each row represents a surface of the optical system (telescope) starting from the source and ending at the surface of the image [13]. While each column represents the characteristics of each surface such as the radius curvature of the surface, thickness, type of glass, the diameter of the pupil aperture, and the conic factor [14].

The binocular telescope consists of a relatively large objective lens, This lens consists of two contact lenses; the first is a biconvex lens made of glass (N-BK7) and the second is a positive meniscus lens made of glass (SF2) The radii of the first lens are ($r_1=155$ mm, $r_2=-100$ mm), while the radii of the second lens are ($r_1=-100$ mm, $r_2=-302$ mm).

The objective lens receives the light rays coming from the object to pass through it into the telescope [15]. The diameter of the pupil aperture of the objective lens must be taken into account because it is one of the important factors for determining the amount of light received by the object. When the diameter of the pupil aperture increases, the amount of light reaching the telescope will increase (**Figure 2**).

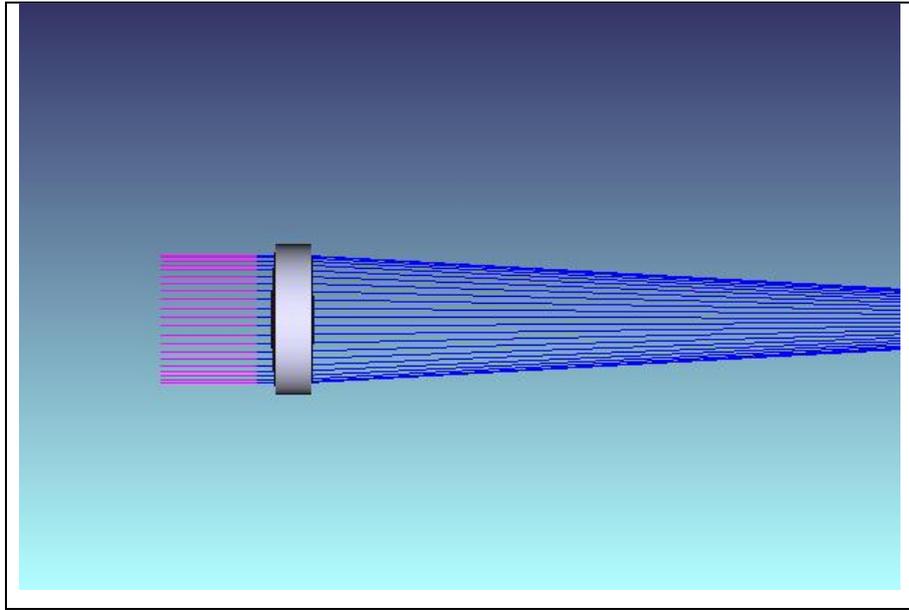


Figure 2. achromatic objective lens of the binocular telescope

The second component of the telescope is a Porro prism, which has a triangular base of a vertical angle (90° , 45° , 45°) consisting of a type of glass (N-BK7)[16]. There are two in the telescope, one perpendicular to the other, in a position that allows the light to change path at an angle of (90°) to reach the eyepiece. The main purpose of placing the prism is to change the path of the rays to reduce the length of the telescope to become portable.

The third component of the telescope is the planar convex lens is a relatively small lens that is placed behind the prism, with the task of collecting the rays coming from the prism to reach the eyepiece lens regularly, used of glass type (N-BK7) to manufacture this lens with radii ($r_1=\infty, r_2=-25\text{mm}$) as shown in **Figure (3)**.

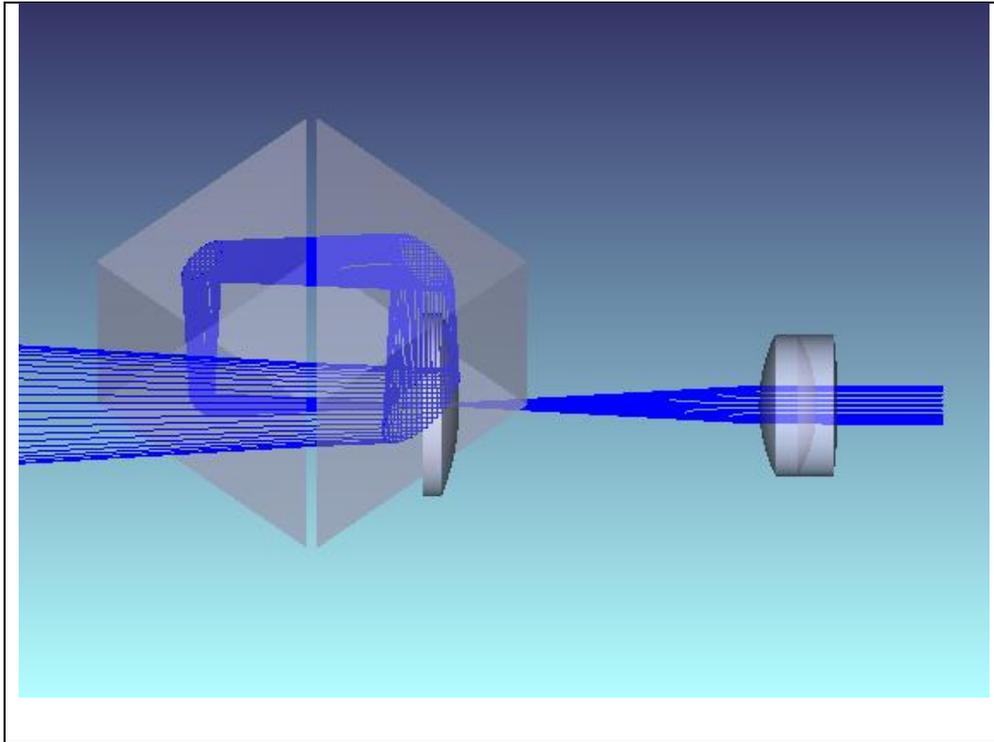


Figure 3. Porro prism, plano-convex lens and eyepiece of the binocular telescope

The fourth component of the telescope is the achromatic eyepiece lens, which consists of two contact lenses, the first lens is a biconvex lens, made of type glass (N-BK7), and the second is a positive meniscus made of type glass (SF5), to get the largest amount of light possible from the object. The radii of the first lens are ($r_1=16\text{mm}$, $r_2= -14\text{mm}$), while the radii of the second lens are ($r_1=-14\text{mm}$, $r_2= -58\text{mm}$). The idea of using a double lens is to eliminate chromatic aberration first, and to adjust the image position secondly.

4. Results

The optical design needs a way to evaluate its performance, as this is the second step in the design stage. A binocular telescope is a tool for image formation, so the performance of the telescope can be evaluated by analyzing the quality of the image formed by it.

Zemax program provides many tools for image analysis, which give a clear idea of the characteristics of the formed image, the amount of aberration, and the extent to which it is affected by diffraction. Through these tools, it is possible to know the performance quality of the designed telescope.

The most important tools used in the Zemax program are the point spread function PSF, the ray fan aberration curves, the optical path difference OPD, the optical transfer function OTF and the encircled energy. PSF shows the intensity distribution of the point object in the image plane, according to the Rayleigh criterion for image quality. Ray fan aberration curve and the OPD show the amount and type of aberration present in the image resulting from the optical system, through which it is possible to give optimal balance values for the optical parameters to reduce the aberration to the lowest value. OTF represents the amount of contrast in the image according to the spatial frequency of the light rays received from the source. As for the collected energy, it gives an idea of the distribution of the energy of the light rays in the image plane according to a central division in the form of circular sectors starting from the center and ending at the edges.

The effective focal length varies by changing the focus separation (s) to different values (160mm, 155mm, 150mm, 145mm, 140mm, 135mm and 130mm). PSF changes clearly according to the change in the focal length and field of view as a result of the focal shift of the image plane. The effective focal length of the ideal location of the image is represented by the value of the curvature radius (145mm), while the other values is not, the value of PSF decreases as the focal shift increases due to the aberration factor as shown in the **Figure (4)**.

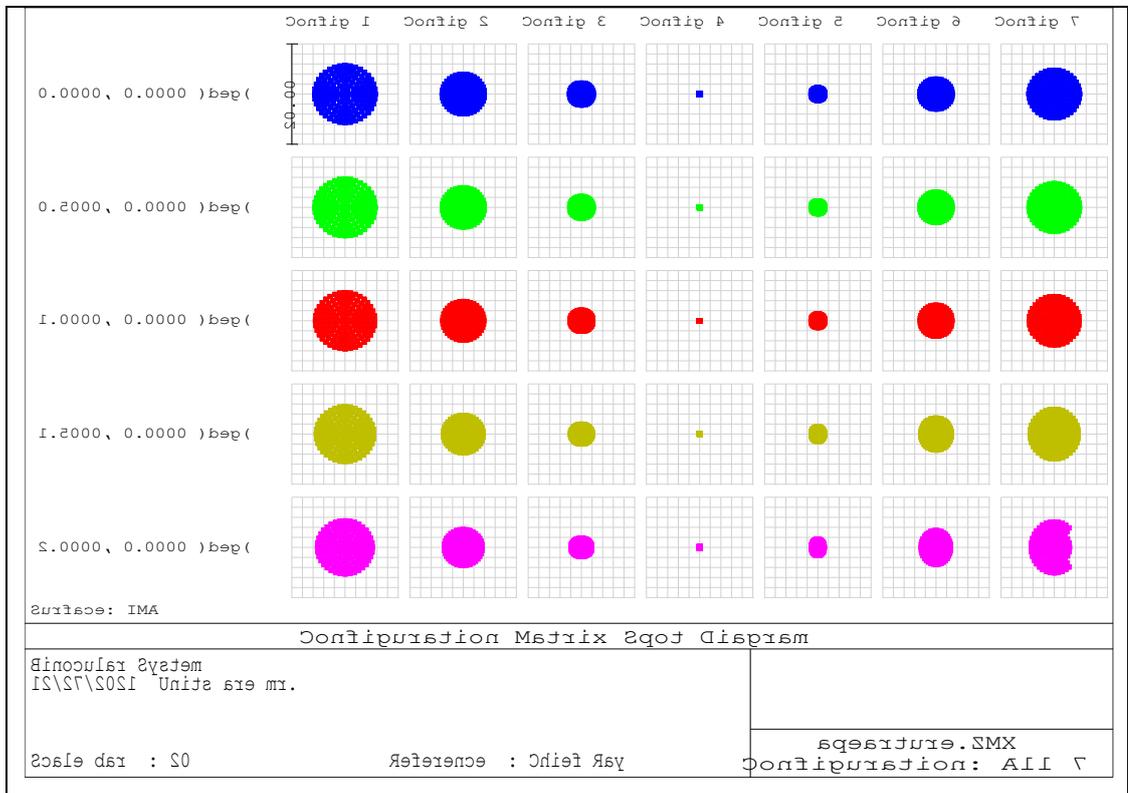


Figure 4. PSF of the binocular telescope in the image plane when the effective focal length changes for variable values of the field-of-view angle

Figure (5) shows the ray fan aberration curve in the image plane for different values of effective focal length. The figure shows the variation of the aberration curves with the change in the effective focal length values due to the change in the focal shift. Each curve shows the intersection of the rays on the x- and y-axis of the image plane.

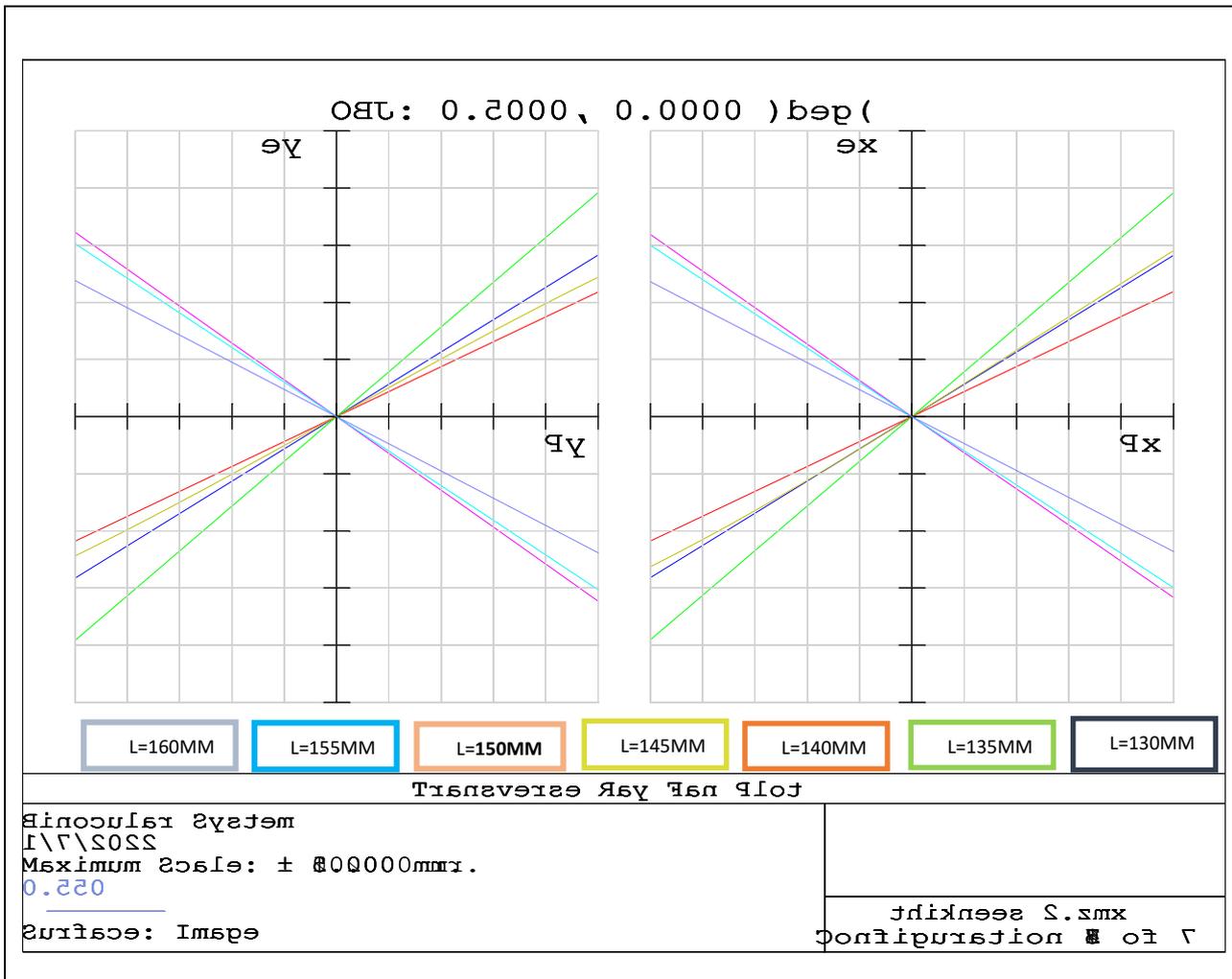


Figure 5. Ray fan aberration of the binocular telescope in the image plane when the effective focal length changes.

OPD curves represent the displacement of the light wavefront path after refraction through the lenses in the telescope. The criterion of the perfect image is through the ideal path of the aberration-free wavefront. The other curves remain the amount of OPD when the focal displacement changes, so the path difference increases with the increase in the effective focal length as shown in **Figure 6**.

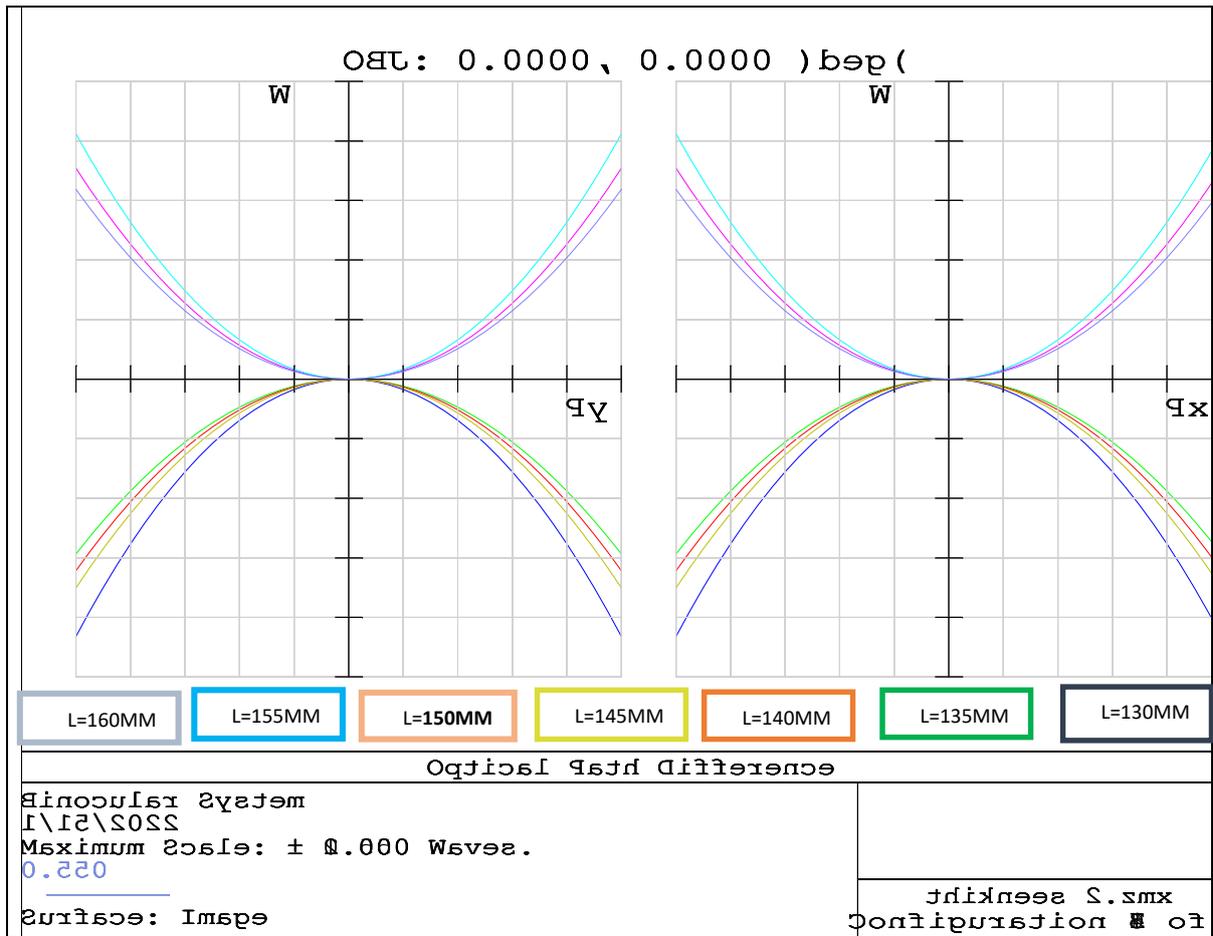


Figure 6. OPD of the binocular telescope in the image plane when the effective focal length changes.

The modulation optical transition function (MTF) determines the amount of contrast in the image about the spatial frequency. **Figure (7)** shows the curves of MTF when the effective focal length of the optical system is changed. The figure shows a variation in the function values when changing the focal shift, where the value of the function decreases clearly with the increase in the value of the spatial frequency. The contrast of the image gradually decreases with the increase in frequency until the image becomes blurred due to the change in the focal shift.

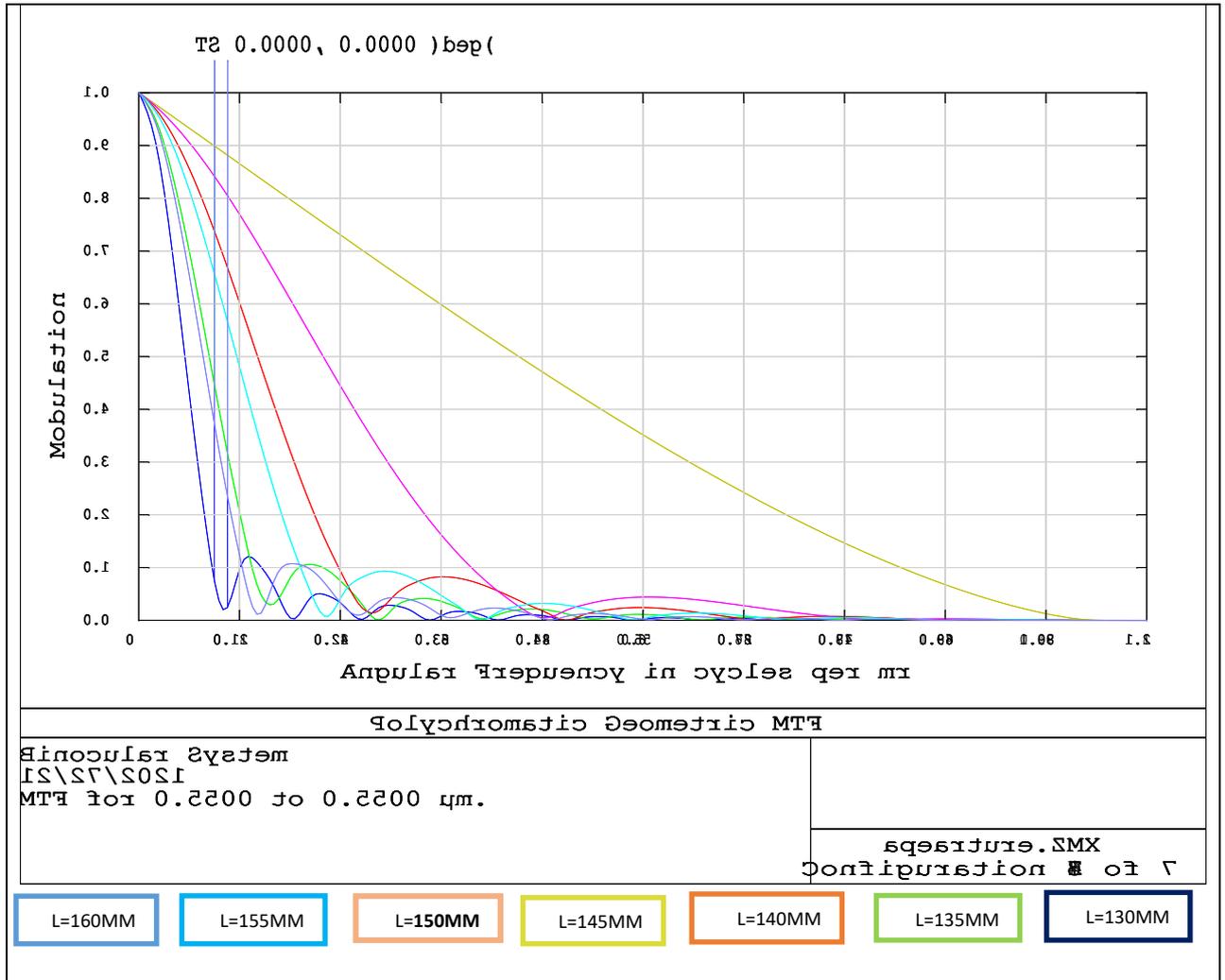


Figure 7. MTF of the binocular telescope in the image plane when the effective focal length changes.

Figure (8) shows the encircled energy curves focused in the image plane when the effective focal length is changed. The curve starts with a minimum value of the radiation energy at the center of the image; this value gradually rises when the central circular sectors increase until it covers all the area of the light rays, so the value of the function is fixed at a certain area. Changing the effective focal length leads to a change in the spread of radiant energy in the image plane to achieve a blurred image of the body.

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