ITMO UNIVERSITY

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OPTICAL SYSTEMS DESIGN: COURSE PROJECT GUIDE

St. Petersburg
2022

MINISTRY OF EDUCATION AND SCIENCE OF THE RUSSIAN FEDERATION

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OPTICAL SYSTEMS DESIGN:
COURSE PROJECT GUIDE

STUDY GUIDE

RECOMMENDED FOR USE AT ITMO UNIVERSITY

within the Master's Program 12.04.02 "Optical Engineering"

St. Petersburg
2022

G.E. Romanova, E.A Tsyganok Optical systems design: course project guide. – St. Petersburg: ITMO University, 2022. – 144 pages.

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The guide contains some basic concepts regarding the optical schemes of telescope (afocal) systems for visual observation. Systems design and methods as well as some specific features of objectives, eye-pieces and inverting systems are discussed.

The guide also contains a detailed step-by-step description of designing the systems, and provides the corresponding examples. Among the examples, systems are considered with a mirror long-focus objective, with a lens inverting system and with a prism inverting system. The guide is intended for the students of the “Optical Systems Design” course, as well as for those who are interested in practical optical systems design.

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Content

Introduction

Telescope systems are widely used for visual observation of various targets and can also be components of more sophisticated devices.

The material presented in this guide describes briefly the general theory of telescope systems, including schemes with an inverting lens or prism systems. It also discusses the features of layout design, the choice of components and aberration correction. The examples given for several options of designs show the practical implementation of some basic ideas and provide a deeper understanding of the material.

Simple two-component telescopic systems

Telescope systems are normally used to observe distant objects. They are widely employed as devices for observing stars, searching targets on Earth, measuring sizes, as pats of geodesic instruments, and for other civil and defense applications.

Such systems do not focus a parallel beam of rays, so they are often called afocal. The simplest example of an afocal system is an afocal lens (see Figure 1) [1].

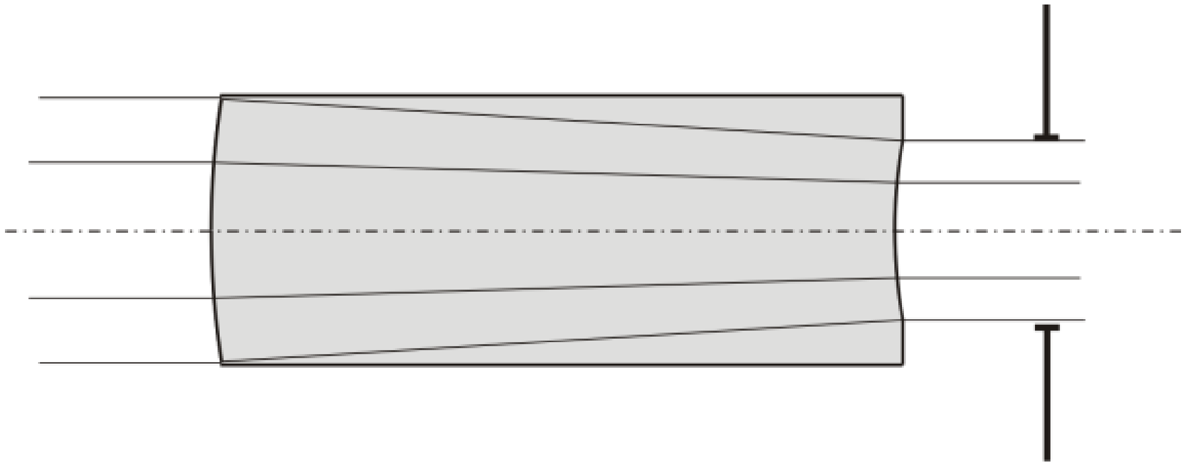


Figure 1 – Afocal lens

A single afocal lens, as a rule, has a large amount of aberrations, moreover, such a lens of adequate dimensions, and with a pupil diameter, which is necessary for practical use, could provide a rather small magnification.

Thus, for practical purposes, two-component systems are used more often where the back focal point of the first component coincides with the front focal point of the second component. The first component is referred to as the objective and the second one is the eye-piece (ocular). There are two variants of the two component scheme, one of them contains two positive components, and the other one contains a positive objective and a negative eye-piece [2-4].

The system consisting of two positive components is referred to as a Keplerian system (Kepler telescope, or astronomical telescope). The system layout is presented in Figure 2.

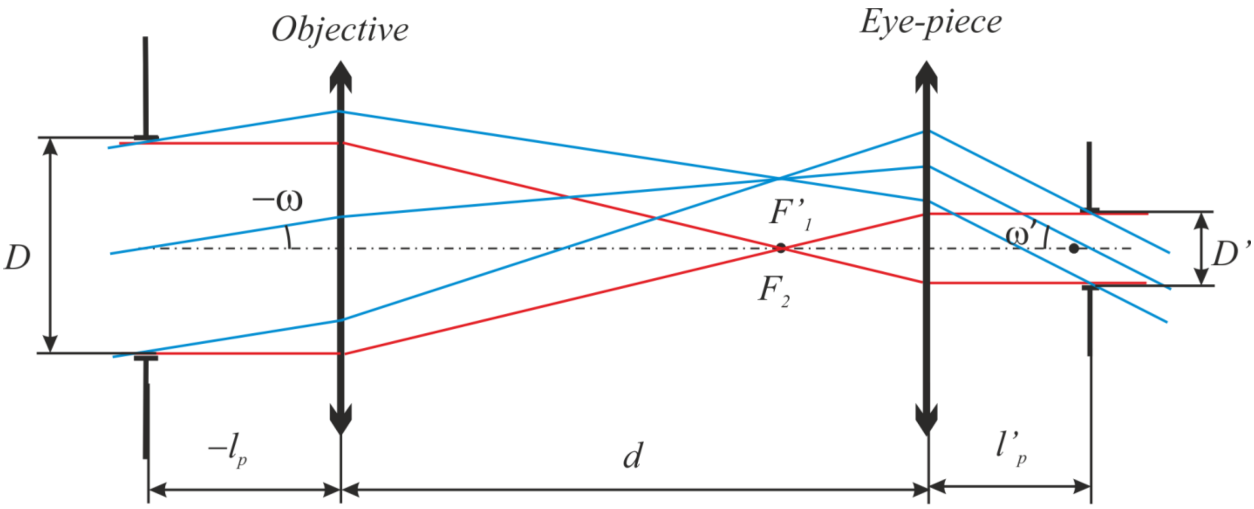


Figure 2 – Layout of a Kepler telescope system

The system of the second type consists of a positive objective and a negative eye-piece and is referred to as the Galilean system (see Figure 3).

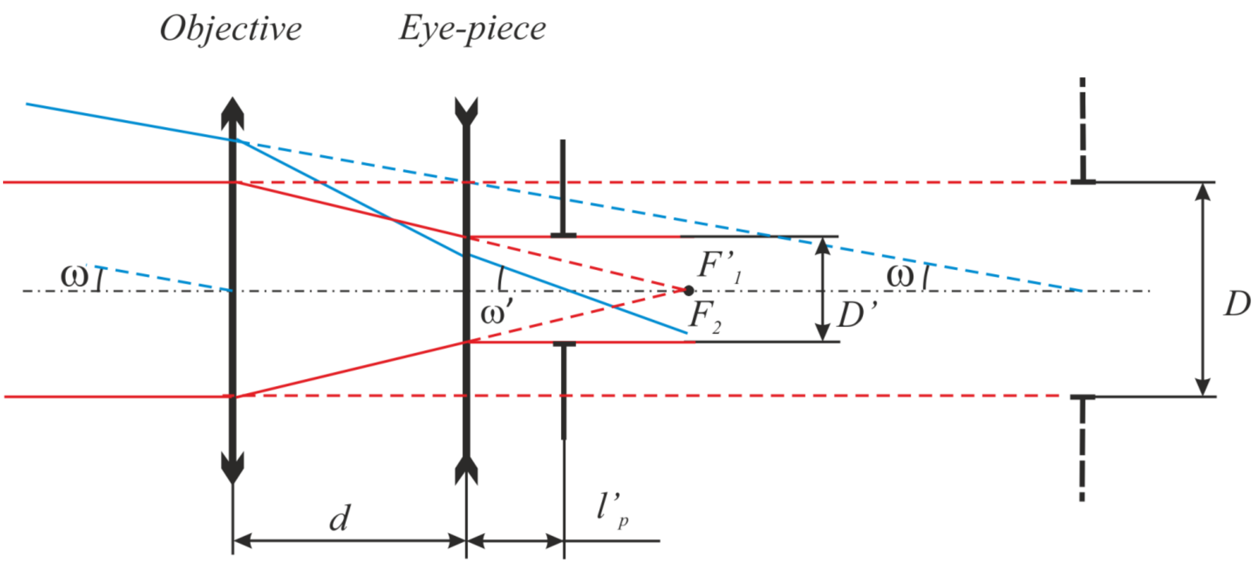


Figure 3 – Layout of a Galilean telescope system

The angular magnification of a two-component telescope system can be described by the following formula:

$$\Gamma = \frac{\mathrm{tg}\,\omega'}{\mathrm{tg}\,\omega} = -\frac{f'_1}{f'_2} \qquad (1)$$

Here f'_1 is the focal length of the first component (the objective), f'_2 is the focal length of the second component (the eye-piece), ω, ω' are the field angles of the system in the object space and in the image space, respectively. The angular magnification of a telescope system is one of its main characteristics, it shows how much closer the objects will seem when observed through the system.

The length of the system in this case is defined by the sum of the components focal lengths:

$$d = f'_1 + f'_2 \qquad (2)$$

As can be seen from Formulas (1) and (2), Kepler telescope type has a negative magnification, thus, the image is inverted, hence, it is normally used for astronomical observations. To use it for other purposes it is necessary to add an inverting system – a lens relay or a prism inverting system. The advantage of this system type is the existence of a real intermediate image where a reticle can be located allowing measuring objects. Also, as can be seen from Figure 2, if the aperture stop is located near the objective, the exit pupil is real and is located after the system, where a human eye is placed during the observation.

The Galilean system is more compact (with the same magnification), but if the exit pupil is real, the entrance pupil is imaginary and is located at a significantly long distance from the system. The position of the entrance pupil relative to the objective l_p can be calculated according to the following formula:

$$l_p = (\Gamma - 1) f'_1 + \Gamma^2 a'_p \qquad (3)$$

Expression (3) shows very clearly that if the system has a large magnification, the entrance pupil will be located at a long distance from the system.

The diameter of the objective (if there is no vignetting) can be calculated as:

$$D_{ob} = 2 l_p \tan \omega + D \qquad (4)$$

Formula (4) shows that even with a moderate value of the angular field, the objective diameter grows linearly with the entrance pupil position. Taking into account Expression (3) one can conclude that the objective size grows quadratically with the increase of the angular magnification.

Thus, this system can provide a moderate magnification value for visual observations (up to approximately 3.5), and a relatively small angular field.

Besides, it has no real intermediate image, so it is not used for measuring. A typical example of applying the Galilean systems is theater glasses.

A separate class of telescope systems is a group with image intensifiers that can be used in the night or in low brightness conditions. In these systems, an image intensifier does not only work as a device which provides a brighter image (and also within a different bandwidth), but also inverses the image at the same time.

The diameters of the entrance and the exit pupils are related as follows:

$$|\Gamma| = \frac{D}{D'} \quad (5)$$

The diameters of the first component (the objective) D_1 and the second component (the eye-piece) D_2 are:

$$D_1 = 2|l_p| \operatorname{tg}\omega + D \cdot (1 - K_v), \quad (6)$$

$$D_2 = 2|l'_p| \operatorname{tg}\omega' + D' \cdot (1 - K_v). \quad (7)$$

Here l_p, l'_p are the entrance and the exit pupil positions, K_v is the vignetting coefficient.

Vignetting means that the beam of rays coming from non-axial points of the object are cut off (for instance, because of lens mounts), and the sloping beams do not fill the entrance pupil fully, but only with the size D_v, which is smaller than D. The vignetting coefficient can be described by the expression:

$$K_v = \frac{D - D_v}{D}. \quad (8)$$

Such geometric vignetting leads to a lower illuminance at the edge of the image, but helps to cut off the rays with large aberrations. It also leads to smaller diameters of components, thus helping to provide smaller sizes.

Resolution and useful magnification

The resolution limit in the object space of a telescope is defined by the entrance pupil diameter D:

$$\psi = \frac{1{,}22\lambda}{D} \quad (9)$$

Here ψ is the angular distance between the two point objects, which can be seen separately.

This formula directly follows from the Rayleigh resolution expression. It refers to the situation when the distance between the two point objects has such a value that the first dark ring of the diffraction image for one of the points coincides with the central maximum of the diffraction image for the second point.

If we use visual spectrum and take into account that the eye can distinguish the contrast of about 5%, then the formula above can be converted to the form:

$$\psi = \frac{120''}{D[mm]}. \qquad (10)$$

Here, if we use the entrance pupil diameter in millimeters, the result is in arc-seconds.

The second factor that can define the resolution of the system is the detector properties – the resolution of the human eye.

The angular resolution in the object space ψ and in the image space ψ' (in the space of the eye) are related by the formula of angular magnification:

$$\Gamma = \frac{\tan\psi'}{\tan\psi} \approx \frac{\psi'}{\psi}. \qquad (11)$$

Using this formula we can calculate the angular resolution in the object space, which corresponds to the eye resolution:

$$\psi_{eye} = \frac{\psi'}{\Gamma}. \qquad (12)$$

If we use ψ' = 60", then

$$\psi_{eye} = \frac{60''}{\Gamma}. \qquad (13)$$

In an optimal case, both resolution values – the one related to the eye properties, and the diffraction limit – correspond to each other.

Using formulas (10)-(13) we can find that the diffraction limit resolution equals the eye limit resolution, if the condition $\Gamma = 0.5D$ is met..

However, for a more general case, the magnification that provides correspondence between the diffraction limits and the eye properties (useful magnification) lies in the range:

$$0{,}2D \le |\Gamma_{useful}| \le 0{,}75D \quad (14)$$

This formula helps to define the adequate angular magnification to achieve the necessary resolution.

Diopter adjustment

As shown above, for a relaxed viewing of distant objects, the back focal point of the objective and the front focal point of the eye-piece coincide.

In the case of short-sighted or far-sighted eyes, relaxed viewing appears in the case of a small shift between the focus of the eye-piece and the focus of the objective.

If we characterize the power of shortsightedness or farsightedness by the value A (in diopters), then the displacement of the eyepiece with the focal length f'_{oc} compared to its nominal position for normal eye (foci coincide) is:

$$\Delta z_{[mm]} = \frac{A_{[dioptres]}}{1000} f'^{2}_{oc[mm]}, \quad (15)$$

Here $A > 0$ for short-sighted eyes, and $A < 0$ for far-sighted eyes, the sign of the displacement shows if it is necessary to move the eye-piece closer to the objective, or to move it away from the objective.

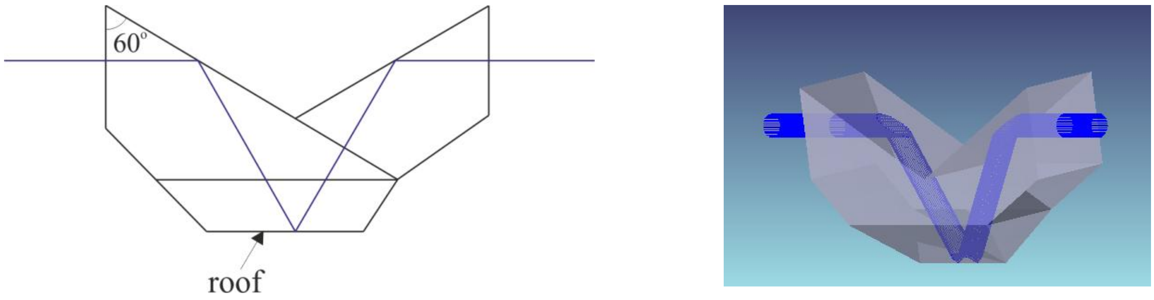
We can also move the eye-piece for observing objects, which are located at a finite distance from the system. In this case, for relaxed viewing by normal eyes the movement value will be equal to the distance of the intermediate image after the objective from the back focal point of the objective.

Telescope with a lens inverting system (with relay optics)

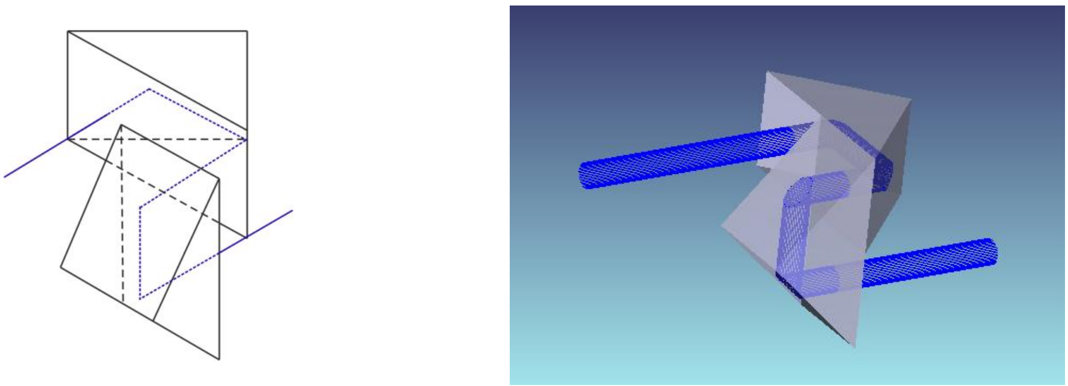
As mentioned above, a simple Kepler system consisting of two components can provide large angular magnification, however, the image is inverted, so it can be applied directly only for observing astronomical objects. Thus, to invert the image in a telescope, additional systems are often used: a prism system or a lens inverting system (a lens relay system).

Some examples of prism inverting systems are shown in Figure 4 [3,5]: Figure 4a shows an Abbe prism with a roof, in Figure 4b a Porro type I system is shown.

Systems based on reflecting prisms work similarly to mirror systems and help change the direction of light propagation, to invert an image, to obtain more compact dimensions of the device. However, compared to mirrors, prism systems have a larger weight and may add aberrations. Among the advantages of prism systems, it is important to mention the stability of the angles between the reflecting faces during instrument operations.



a



b

Figure 4 – Prism systems: a) Abbe prism with a roof, b) Porro system (type I)

Another option to invert an image is to use a lens inverting system that works as a lens relay projecting the image after the objective to the focal plane of the eye-piece.

One of the most widely used is a symmetric lens inverting system with parallel ray paths between the components. The system of this type is shown in Figure 5. The aperture stop is located in the middle of the distance between the components.

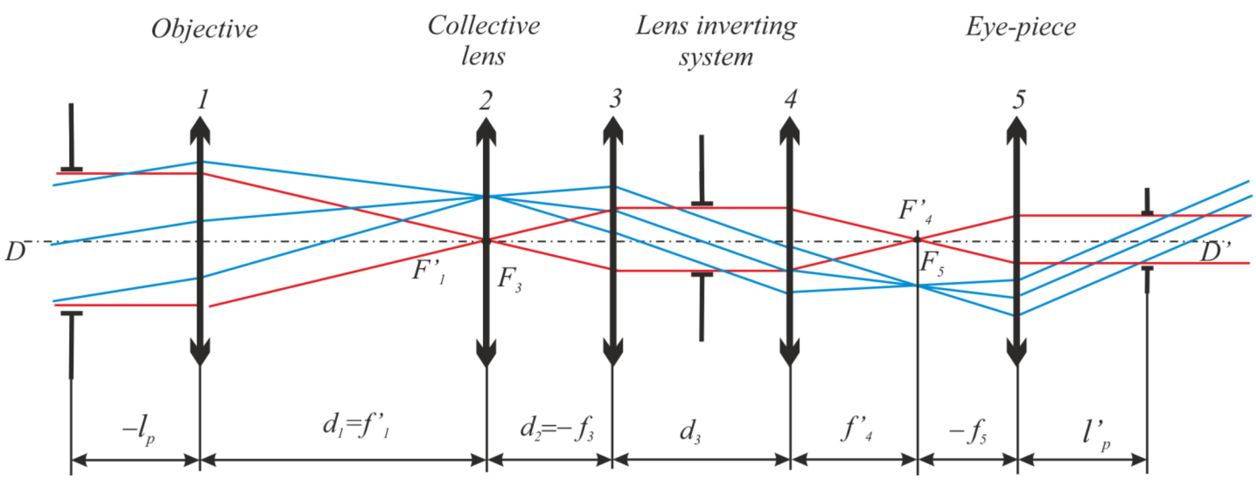


Figure 5 – Telescope system with a two component lens inverting system: 1 – objective, 2 – collective lens (field lens), 3,4 – components of the lens inverting system, 5 – eye-piece

A two-component inverting system with parallel ray paths between the components has some advantages from the point of view of aberrations correction: the symmetry of the system relative to the aperture stop when working with the magnification $V = -1$ leads to a compensation for some aberrations (coma, distortion, lateral color) and thus, to a simpler design of the system. An additional component is usually placed near the focal plane of the objective (see component 2 in Figure 5). This component is referred to as a collective lens and is necessary in the system to get smaller diameters of components and the required pupil position.

The angular magnification of the telescope system with a lens inverting system can be described by the formula:

$$\Gamma = -\frac{f'_1}{f'_5} V_{LIS}, \qquad (16)$$

where f'_1 is the focal length of the objective, f'_5 is the focal length of the eye-piece, V_{LIS} is the linear magnification of the image by the lens inverting system. Expression (16) is valid for the case when the magnification of the collective lens (field lens) is $V_{col} = 1$, that is, for the situation when the collective lens is placed near the intermediate image plane.

The linear magnification of the lens inverting system (relay system) V_{LIS} for the case shown in Figure 5 for parallel ray paths between the two components is:

$$V_{LIS} = -\frac{f'_4}{f'_3}, \qquad (17)$$

where f'_3, f'_4 are the focal lengths of the components of the lens inverting system.

If technical assignments state requirements for the maximum diameter of the lenses in the telescope system D_0, then for finding the necessary primary characteristics of the components, the following expression can be used:

$$f'_1 = \frac{D_0}{2\tan\omega}, \tag{18}$$

where ω is the field angle in the object space.

The focal length of the first and the second components of the lens inverting system f'_3 and f'_4 can be found using the formulas:

$$f'_3 = \frac{D_0}{D} f'_1, \tag{19}$$

$$f'_4 = \Gamma \frac{f'_3 \, f'_5}{f'_1}. \tag{20}$$

In a general case, for an arbitrary vignetting coefficient, the distance between the components of the lens inverting system d_3 can be calculated as:

$$d_3 = 2K_V f'_3 = \frac{K_V D_0^2}{D\tan\omega}. \tag{21}$$

If we assume a 50 % vignetting ($K_v = 0.5$) in the system, then $d_3 = f'_3$.

If technical assignments set requirements for the length of the telescope L , that is, the distance from the objective to the eye-piece, then a calculation of the necessary characteristics can be implemented as follows: if we know the value of the magnification of the lens inverting system and the vignetting coefficient (or can select these values) the diameters of the components D_0 can be found from the equation:

$$2L\tan\omega = \frac{1 - V_{LIS} + 2K_V}{D} D_0^2 - \frac{\Gamma - V_{LIS}}{\Gamma} D_0. \tag{22}$$

For the value K_v=0.5 (50% vignetting) and the magnification $V_{LIS} = -1$ the system length is:

$$L = \frac{3D_0^2}{2D\tan\omega} + \frac{D_0(\Gamma + 1)}{2\Gamma\tan\omega}. \tag{23}$$

Thus, there are some methods of finding the focal lengths of all components of a telescope. As mentioned above, the collective lens in the system is placed near the focal plane of the objective. It is necessary to match the pupil position for the two parts of the system. At the final stage, the focal length of the collective lens is calculated in the way that given the real aperture stop is in the middle of the distance between the components of the inverting system, we can obtain the required value of the entrance pupil position.

One of the methods for finding the collective lens focal length uses the calculation of the chief paraxial ray (shown in blue in Figure 6 below).

General formulas for the calculation of the chief paraxial ray are the following:

$$H_{i+1} = H_i - \tan\omega_{i+1} d_i \,, \tag{24}$$

$$\tan\omega_{i+1} = \tan\omega_i + H_i \Phi_i \,. \tag{25}$$

In expressions (24), (25) H_i, H_{i+1} are the chief ray heights on the principal planes of the components *i* и *i+1*, respectively, d_i is the distance between the components *i* and *i+1*, ω_i, ω_{i+1} is the chief ray angle relative to the optical axis before and after the component *i*, Φ_i is the optical power of the component *i*.

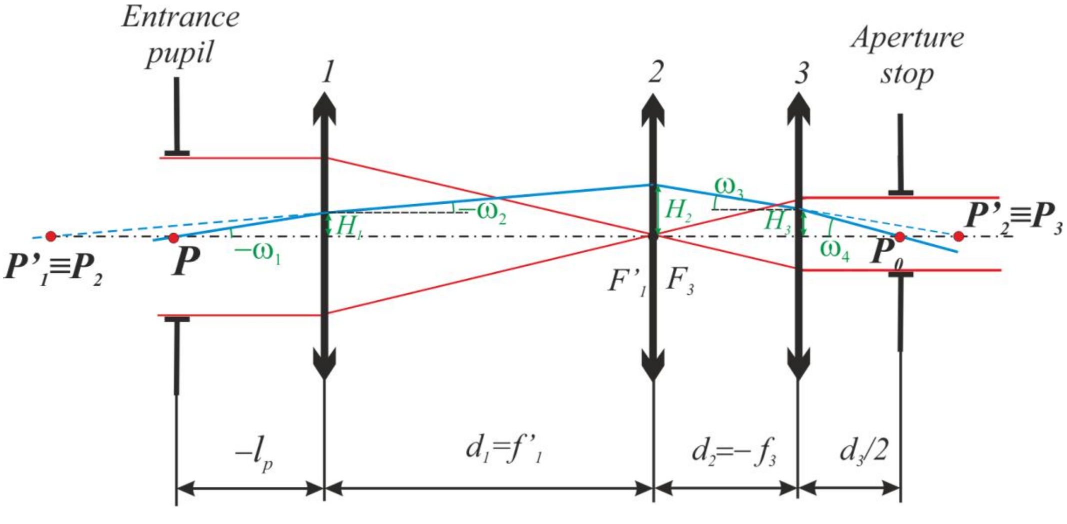


Figure 6 – First part of a telescope system with a lens inverting system: 1 - objective, 2 - collective lens, 3 - the first part of a symmetrical lens inverting system

Using general equations, for the case under consideration, we can rewrite as:

$$H_1 = l_p \tan\omega_1 \,, \tag{26}$$

$$\tan\omega_2 = \tan\omega_1 + H_1\Phi_1, \quad (27)$$

$$H_2 = H_1 - \tan\omega_2 d_1 = H_1 - \tan\omega_2 f'_1 = -\tan\omega_1 f'_1, \quad (28)$$

$$\tan\omega_4 = H_1\Phi_3, \quad (29)$$

$$H_3 = \frac{d}{2}\tan\omega_4 = H_2 - \tan\omega_3 f'_3, \quad (30)$$

$$\tan\omega_3 = \frac{H_2 - H_3}{f'_3} \quad (31)$$

Thus, the optical power of the collective (field) lens is:

$$\Phi_2 = \frac{\tan\omega_3 - \tan\omega_2}{H_2}, \quad (32)$$

Or, the focal length of the collective lens is:

$$f'_2 = \frac{H_2}{\tan\omega_3 - \tan\omega_2}. \quad (33)$$

The method described above can be used for the case when the telescope objective has a relatively simple design and may be considered as a thin component.

Alternatively, the focal length of the collective lens could be calculated based on the following concepts. If we know the distance between the components of a symmetrical lens inverting system d_3 and the focal length f'_3 of the component 3, we can consider the aperture stop as the exit pupil for the component 3 with the position l'_{p3} and find its entrance pupil position l_{p3} (see Figure 7) using expressions of paraxial optics. This pupil will be the exit pupil for the component 2, and the pupil distance from the component 2 is:

$$l'_{p2} = f'_3 + l_{p3} \quad (34)$$

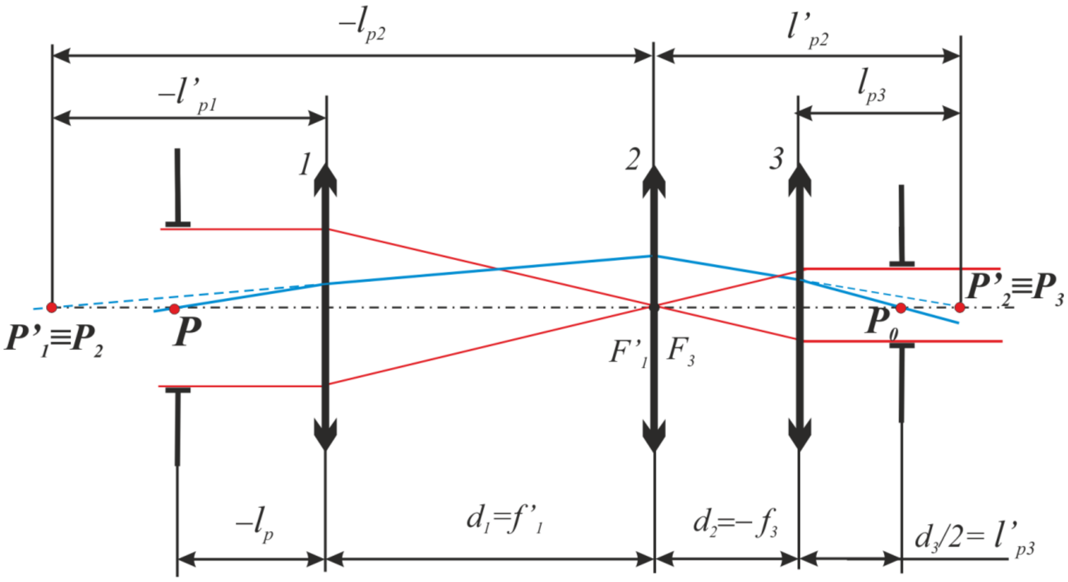


Figure 7 – Paraxial pupil positions in the first part of the telescope system with a lens inverting system

On the other hand, if we know the required position of the entrance pupil related to the component 1 (the objective) $l_p = l_{p1}$, we can find the exit pupil after the objective l'_{p1}. This pupil is the entrance pupil for the component 2 and its position is:

$$l_{p2} = l'_{p1} - f'_1. \quad (35)$$

Thus, for the component 2 the entrance and the exit pupil positions are known, so using Formula $1/f'_2 = 1/l'_2 - 1/l_2$ we can find its focal length.

Optical components

The main components of a telescope system are an **objective** and an **eye-piece**. Depending on the necessary characteristics, both components could have various structures.

The simplest objective type is a cemented doublet, where one of the lenses has a positive optical power and is made of crown glass, while the other lens has a negative optical power and is made of high dispersion flint glass. This provides the correction of the axial color with the positive optical power of the entire system. By choosing the appropriate shape of the lenses, it is possible to correct both the spherical aberration and the coma. In the cemented doublet which is an achromat, a proper aberration correction is achieved for systems with apertures up to f/5…f/4 and an angular field of $2\omega \leq 10°$ (at $f'_1 \leq 200$ mm).

An air-spaced doublet can also be applied as an objective: it provides a better correction of the aberrations, and can work with apertures up to f/2.5 … f/3.

Simple schemes of the objectives are shown in Figure 8.

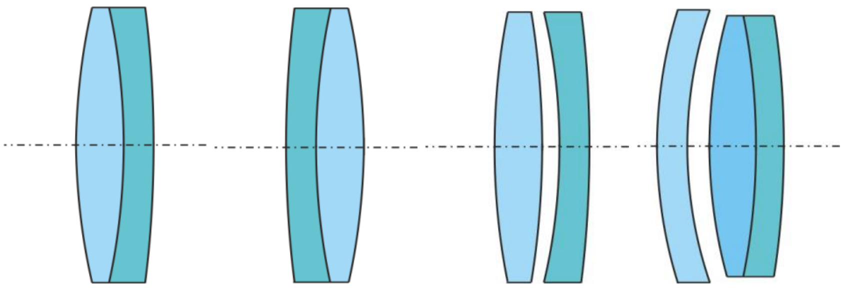


Figure 8 - Simple schemes of objectives used in telescope system

Some examples of the objective design as well as aberrations can be found in [3].

In the cases where the total length of the system is crucial a *telephotolens* scheme is used: the total length of the system L is smaller than its focal length. In this case, the objective consists of two components – the positive and the negative ones (see Figure 9) [6].

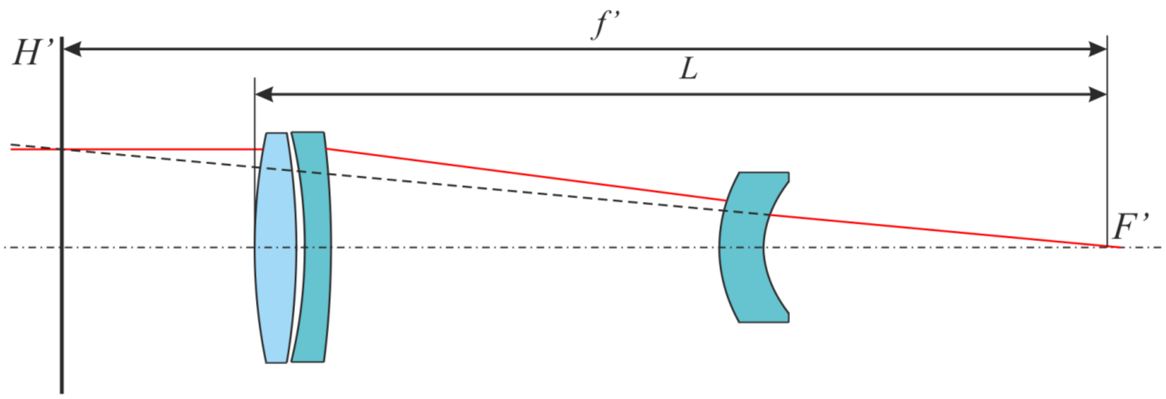
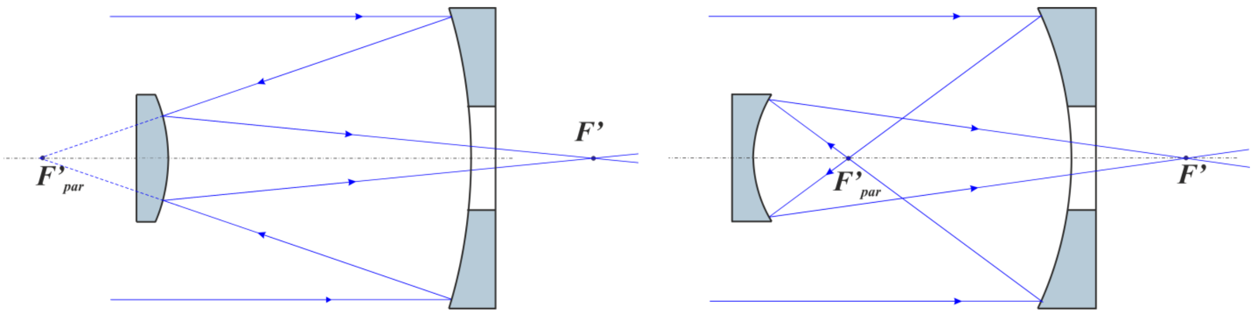


Figure 9 – Scheme of a telephotolens

For telescope systems used in amateur astronomy *mirror systems* are widely used: their main advantage is that their length is much smaller compared to their focal length which has to be large for astronomical purposes. They have no chromatic aberrations either, however, it is necessary to apply aspherical surfaces to provide a high image quality. The second feature worth mentioning is the obscuration. It takes place in most mirror systems and leads to energy losses and lower resolution. The obscuration is unavoidable in the mirror systems with axial symmetry and is usually described by the ratio of the diameter of the secondary mirror, which defines the blocked region, and that of the primary mirror.

The most well-known Cassegrain and Gregory schemes [2, 3, 7] include a parabolic primary mirror and a hyperboloid or an ellipsoid secondary mirror (convex or concave, respectively – see Figure 10). The Cassegrain and Gregory schemes are designed as a combination of a parabolic mirror with a convex or concave mirror, where one of the geometric foci (free of spherical aberration) of the secondary mirror generating curve coincides with the focal point of the parabola. Thus, the schemes are free only from spherical aberration and provide an adequate image quality within a very small field.

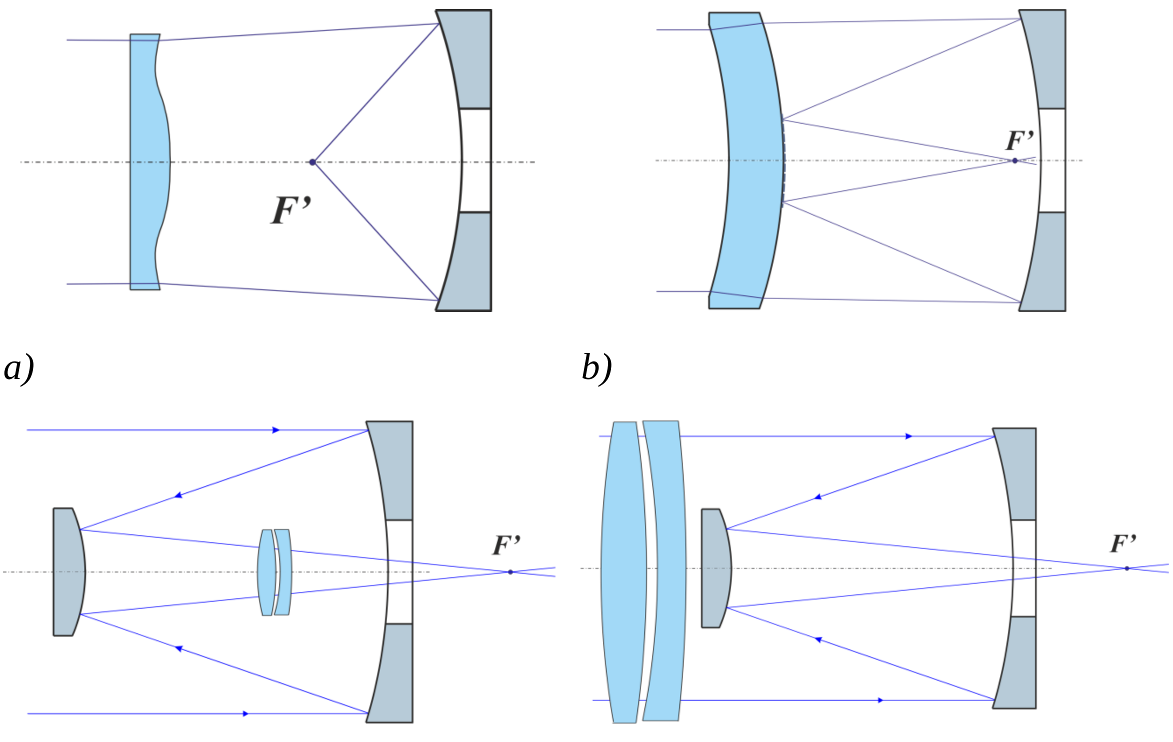


a) *b)*

Figure 10 – Classical mirror objectives: a) Cassegrain system, b) Gregory system

In a design known as a Richie-Chrétien system, both the spherical aberration and the coma are corrected, and the surfaces are hyperboloids (in a secondary convex mirror design).

Catadioptric objectives (mirror systems with lens correctors) [8] are also widely used in telescope systems, especially for amateur astronomy. These systems have some of the advantages of pure mirror systems (small length) and some of the disadvantages (obscuration). These systems can provide a high image quality with a smaller number of aspherical surfaces or even with spherical ones only, which is efficient from the point of view of manufacturability [4]. Several examples of the catadioptric schemes are presented in Figure 11: in many cases correctors with a relatively small optical power are used, namely, the Schmidt plate (Fig.11a), the Maksutov's meniscus (Fig. 11b), the two-lens afocal corrector placed in a converging beam of rays after the reflection by the secondary mirror (Fig.11c), the two-lens afocal corrector that is placed before the system in a parallel beam of rays (Fig. 11d).



a) *b)* *c)* *d)*

Figure 11 – Catadioptric objectives: a) Mirror with the Schmidt plate, b) Maksutov-Cassegrain system; c) Mirror system with a lens afocal corrector in a converging beam; d) mirror system with a lens afocal corrector in a parallel beam

The choice of an objective scheme is determined by many factors – both the required dimensions and the basic optical characteristics (the focal length, the entrance pupil diameter, the working field), the spectral bandwidth, the required image quality, the planned placement, and operating conditions.

The second important component of e telescope systems is the **eye-piece**. This component works with a much larger angular field, thus, depending on the necessary field and eye-relief (the pupil position with respect to the eye-piece) the appropriate scheme type can be chosen.

The eye relief is a very important characteristic; it has to be at least 10 mm to guarantee some space for the lashes. If a user wears spectacles, the minimum distance comfortable for the user is 20 mm. For riflescopes this distance may reach 70 … 80 mm and more [4].

Table 1 gives some characteristics of several eye-piece types [9, 10, 11, 12], thus, as the angular field and the possible eye-relief strongly depend on the system type, both these characteristics have to be considered when choosing the appropriate eye-piece scheme. In the table, the eye-relief is given in the scale of the focal length, both the eye-relief and the angular field in the table are typical values and may slightly vary for a certain eye-piece scheme.

Table 1. Characteristics of eye-pieces

Eye-piece type	*Angular field, $2\omega'$, degrees*	*Relative eye relief, S_P/f'*
Ramsden	30…40	0.25 … 0.3
Kellner	<50	0.5
Symmetrical (Plossl)	40…50	0.75
Orthoscopic	<40	0.75
Erfle I type Erfle II type	65 60…65	0.5 0.5 …0.75
With remote pupil	<45	0.9…1
Wide-angle	76…90	0.48 …0.66

Figure 12 shows several typical eye-piece schemes.

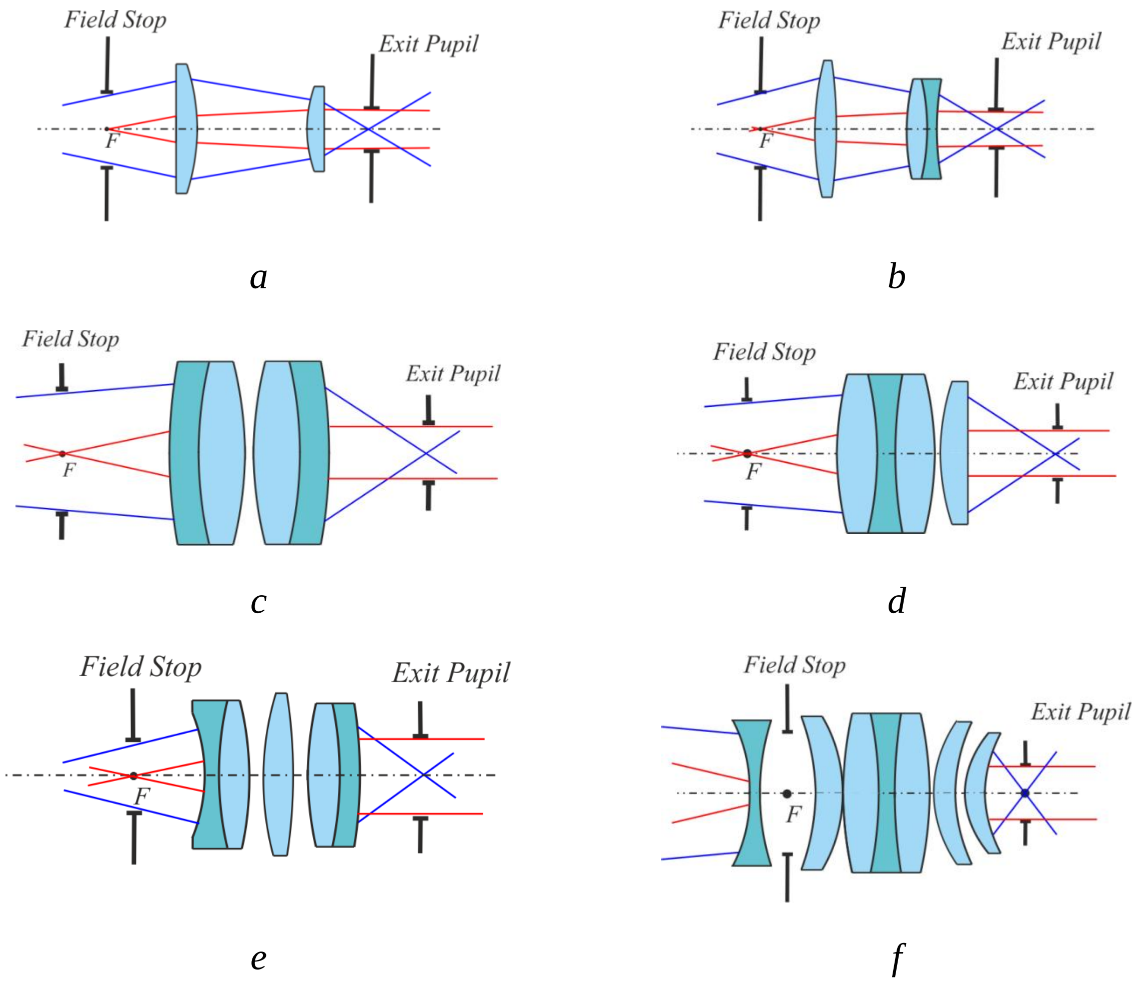


Figure 12 – Eye-pieces: a) Ramsden b) Kellner c) Symmetrical (Plossl) d) Orthoscopic e) Erfle II type f) Wide Angle (Example)

General design procedure

Generally, designing starts with checking the initial data or defining them according to the necessary resolution, dimensions, angular magnification and other characteristics. The designing includes several steps:

- Layout design: defining the focal lengths, pupil positions and diameters, angular fields, total length, and other characteristics of the basic components;
- Choosing the eye-piece;
- Choosing the objective type and designing the objective;
- Composing system together;
- Designing and inserting the inverting system of the chosen type if necessary;
- Evaluating the system performance and optimizing the overall system.

Primarily, the design features of a telescope system depend on the system type: Keplerian or Galilean system, using a lens or a prism inverting system or no inverting system at all in Keplerian type, the type of the objective.

At the stage of the layout design the ideal paraxial components are normally used. During layout designing, the important parameters are calculated and the initial technical assignments can be adjusted in case they lead to a hardly feasible system. For example, if initial data provides components that have low f/numbers and/or high angular fields, this leads to a complicated structure.

Choosing the eye-piece type is usually based on the necessary angular field and eye-relief. For example, simple eye-piece types provide a relatively small angular field, a short focal length system cannot provide a large eye-relief necessary for some instruments.

Choosing the objective type is based on the calculated values of f/number, the desired length and the focal length. For long focal length systems, mirror objectives and catadioptric systems are used.

The inverting system can be of a lens or of a prism type. The application area and the requirements for the system length define the choice of the inverting system type. In some cases, two options of the system are considered, and after designing, a comparative analysis is implemented to choose the optimal solution.

Typically, each optical component of the total system is designed separately. There is a design method where after choosing the eye–piece and the inverting prism system their aberrations are evaluated for their common operation to find the value of the residual aberrations which will be compensated by the objective.

After composing all the components into the entire system it **may be** necessary to optimize the whole system to achieve the necessary image quality.

Below we present the three possible types of systems and discuss the specific features of their design.

A telescope system with a mirror objective

Before choosing the initial scheme it is necessary to choose the objective – a mirror or a lens one. It can be done based on the analysis of its characteristics: if in the individual assignment the diameter of the objective is larger than approximately 100 mm and the focal length larger than 1000 mm, for the project, it is better to use a mirror objective.

The absolute value of angular magnification is given in the assignment. For the design option with a relatively large angular magnification with a mirror objective it is assumed no additional inverting system is used, thus, the system of this type has the negative magnification $\Gamma < 0$. In the formulas below the negative value of Γ is to be used.

1. **1.** Calculate the first-order properties for the system and its components: find the focal lengths of the components, their diameter, F-numbers, and other characteristics using following formulas:

Magnification of the two-component system:

$$\Gamma = -\frac{f'_{ob}}{f'_{ep}},$$

where f'_{ob}, f'_{ep} are focal lengths of the objective and the eye-piece, respectively.

Angular field of view in the object space is:

$$\tan\omega = \tan\omega_{ob} = \tan\omega' / \Gamma .$$

Focal length of the objective:

$$f'_{ob} = D \cdot F\#$$

Focal lengths of the eye-piece:

$$f'_{ep} = -f'_{ob} / \Gamma$$

Exit pupil diameter:

$$D' = D / |\Gamma|$$

F-number of the eye-piece:

$$F\#_{ep} = f'_{ep} / D' .$$

Thus, in this option an objective is considered with the following characteristics:

Focal length f'_{ob} =_____;

Entrance pupil diameter $D_{ob} = D$ = _____;

Angular field of view $2\omega_{ob} = 2\omega$ =_____;

The telescope reversed eye-piece is to have the following characteristics:
Focal length f'_{ep}=_____;
F-number of eyepiece $F\#_{ep}$=_____;
Angular field of view $2\omega_{ep}=2\omega'$=_____;

2. According to the characteristics of the eye-pieces, choose an eye-piece from the catalog:
- The focal length of the eye-pieces selected from the catalog f'_{cat} is not to be more than twice as large or half as small as the necessary focal length f'_{ep}. If the focal length chosen is too small compared to the necessary value, after scaling to the necessary focal length it may lead to a large amount of aberrations that may be difficult to correct. If the focal length is too large compared to the necessary value, after scaling it may result in a undesirably small thicknesses or too small radii;
- $F\#_{cat}$ is to be smaller than $F\#_{ep}$: it guarantees that after scaling, the pupil diameter of the eye-piece will not be smaller than the required value;
- $2\omega_{cat}$ is to be larger than $2\omega_{ep}$.

Include the characteristics of the chosen eye-piece to the report: the characteristics of the eye-piece from the catalog are:
Focal length f'_{cat} =_____;
F-number of the eye-piece $F\#_{cat}$=_____;
Angular field of view $2\omega_{cat}$=_____;

3. Set the eye-piece in Zemax Optic Studio software. Use at least three wavelengths (λ_e = 0.545 μm, $\lambda_{F'}$ = 0.643 μm, $\lambda_{F'}$ = 0.480 μm). Analyze the first-order properties, the layout, the spot diagrams and the aberration plots.

Lens Data of the eye-piece from the catalog:

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
1				
2				
3				
…				
N				

Cardinal points of the eye-piece from the catalog.

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm

Here S_F, $S'_{F'}$ are the focal distances of the system, S_H, $S'_{H'}$ – the principal plane positions with respect to the first and the last lens surfaces of the system

4. Using the instrument "***Make Focal***" from the menu of LDE scale the system to have the necessary focal length.

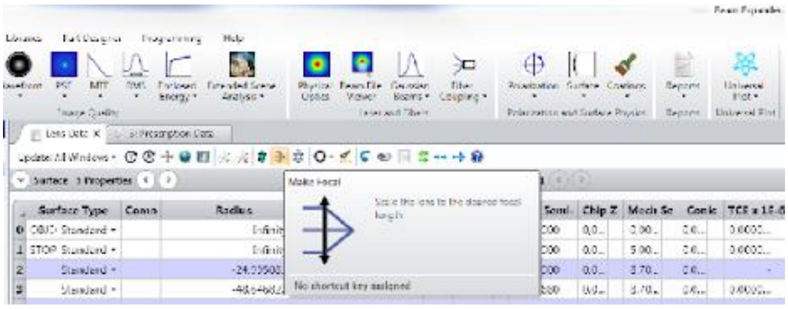


Figure 13 – "Make focal" tool from Zemax Optic Studio

5. Correct the aperture and the field of view: set the values according to the calculations.

Lens Data of the eye-piece (reversed ray path: the object is at infinity)

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
1				
2				
3				
…				
N				

Cardinal points of the eye-piece

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm

Save images and include them in the report:

- Figure 1 – Layout

- Figure 2 – Spot diagrams
- Figure 3 – Ray fan aberration
- Figure 4 – Field Curvature / Distortion

6. **Analyze the image quality of the eye-piece.**

Analyze what types of aberrations can be identified in the system. Analyze the longitudinal aberration plot to identify the axial color, open and save the field curvature/distortion plot to analyze the astigmatism and the field curvature.

Find the spot size diameter for the axial point D_{spot0} . Calculate the angular value of the spot for the image space (in the observer's eye space) using the expression:

$$\Delta\varphi'_0 = \frac{D_{spot\,0}}{f'_{ep}}$$

Find the spot size for the maximum field $D_{spot\,max}$ and calculate the angular value of the spot for the image space:

$$\Delta\varphi'_1 = \frac{D_{spot\,\max}}{f'_{ep}}$$

Here in the formulas, to get the angular value in radians it is necessary to use the spot diameters and the focal length in mm.

7. The next stage is designing the mirror objective [7]. At this stage it is necessary to calculate the two-mirror objective.

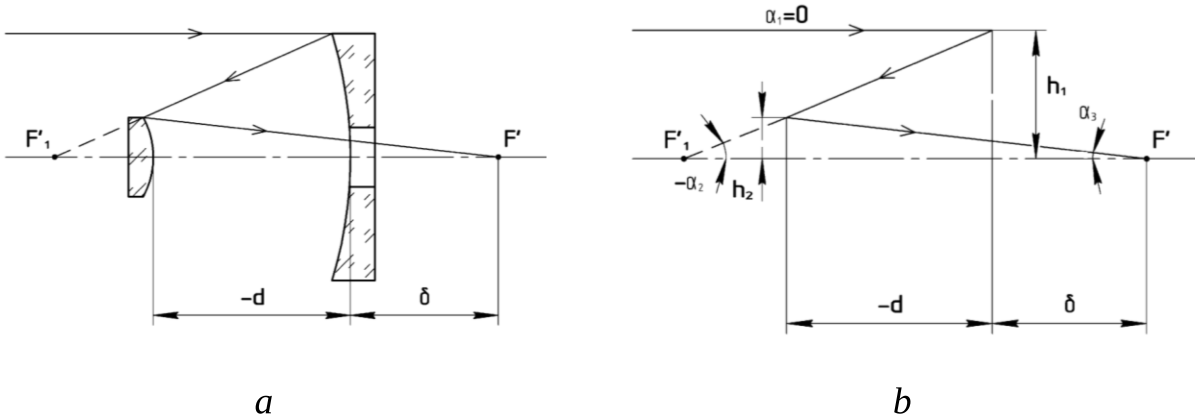


Figure 14 – Two-mirror system: a) Schematic drawing b) principal planes of the mirrors for the first-order calculations: a marginal ray is shown

In Figure 14a, F'_1 is the focal point of the primary mirror, F' the equivalent focal point of the objective, in Figure 14b δ is the position of the image plane with respect to the first mirror surface, d is the distance between the mirrors; h_1, h_2 are the marginal ray heights on the first and second mirrors, respectively.

As mentioned above, the mirror objective of this type has an obscuration that leads

to blocking part of the rays in the center of the pupil.
The obscuration in such a system can be described by the obscuration ratio ε:

$$\varepsilon = \frac{D_2}{D_1} = \frac{h_2}{h_1}$$

The obscuration in the system will lead to a lower transmitted energy and a lower resolution. Thus, this coefficient usually has to be lower than 0.35.
Below we give some expressions, where all linear values (distances, radii) are given in relative units, for the so called normalization condition $h_1 = f' = 1$.

Choose the obscuration coefficient ε = 0.1 – 0.35 and the distance δ in the scale of the focal length $\bar{\delta} = \delta / f'_{ob}$ =0.05 – 0.1
Calculation in relative units:

$$\alpha_1 = 0;$$

$$\alpha_2 = \frac{\varepsilon - 1}{\varepsilon - \bar{\delta}};$$

$$\alpha_3 = 1;$$

$$d = \bar{\delta} - \varepsilon;$$

$$h_1 = 1;$$

$$h_2 = \varepsilon h_1;$$

$$\bar{r}_1 = \frac{2}{\alpha_2};$$

$$\bar{r}_2 = \frac{2\varepsilon}{1 + \alpha_2}.$$

To calculate the radii and the distances in mm multiply the values by the scale coefficient equal to the focal length of the objective:

$$R_1 = \bar{r}_1 \cdot f'_{ob};$$

$$R_2 = \bar{r}_2 \cdot f'_{ob};$$

$$d = \bar{d} \cdot f'_{ob}.$$

8. Set the objective in Zemax Optic Studio software. Analyze the first-order properties and the layout. Analyze the spot diagrams and the OPD plots. Optimize the image quality using conic constants as variables: correct the spherical aberration and the coma. Analyze the image quality of the objective.

Lens Data of the objective

№	Radii	Thickness	Material	Conic
1				
2				

Cardinal points of the objective

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm

Save images and include them in the report:
- Figure 1 – Layout
- Figure 2 – Spot diagrams
- Figure 3 – Ray fan aberration
- Figure 4 – Field Curvature / Distortion

9. Compose the system of the objective and the eye-piece

In the system, the eye-piece is to be reversed to operate in a position where the parallel ray paths are after the eye-piece.

Calculate the distance between the lenses of the objective and the eye-piece:

$$t = S'_{F'ob} + \overleftarrow{S}'_{F'ep}$$

Here $\overleftarrow{S}'_{F'ep}$ is the back focal length of the eye-piece in a reversed ray path (see the Table above for the eye-piece)

Lens Data of the system

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
1				
2				
3				
…				
N				

Check the main characteristics of the composed system: the focal length is to be close to infinite, the angular magnification is to correspond to the value in the individual assignment. Check the layout of the system.

In System Explorer in Aperture settings tick "*Afocal image space*" to analyze the aberrations in angular units (transverse aberrations) and in diopters (longitudinal aberrations):

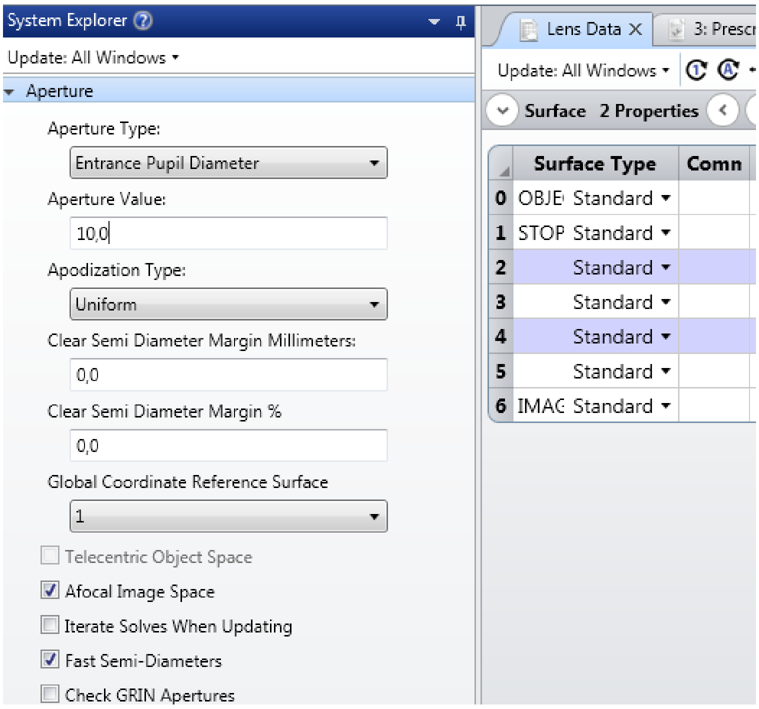


Figure 15 – Afocal image space settings

Save the **General characteristics for the report:**

Angular magnification

Entrance pupil diameter

Exit pupil diameter

Entrance pupil position (with respect to the first lens)

Exit pupil position (with respect to the last lens)

Angular field in the object space

Angular field in the image space

Save for the report:

Figure 1 – Layout

Figure 2 – Spot diagrams

Figure 3 – Optical Path Difference

Figure 4 – Field Curvature / Distortion

10. Analyze the image quality of the system

Analyze the longitudinal aberration plot, the field curvature/distortion plot, the OPD plots and the spot diagrams.

Analyze the maximum spot size (rms and geometric) in angular units. Compare it with the eye-resolution.

Analyze the presence of astigmatism and compare the maximum value of astigmatism in the system with the reasonable allowable value of 3-5 diopters.

Open the MTF plot, find the spatial frequency that corresponds to the contrast ratio of 0.2 for the axial point (ν'_0) and for the maximum field (ν'_1). Calculate the resolution for the object space in angular units:

$$\psi = \frac{1}{\Gamma \cdot \nu'}$$

It is worth noting that this calculation does not take into account the accommodation possibilities of the human eye.

11. Check the exit pupil position in the system

Analyze the layout of the system from the point of view of pupil positions with respect to the surfaces of the system: the entrance pupil is to be located near the first surface of the objective, the exit pupil position is to be close to its focal plane.

If, for the case of aperture stop located on the primary mirror, the exit pupil shifts from its desired position, calculate the parameters of the collective lens that has to be placed in the intermediate image plane.

The role of the collective lens is to conjugate the pupil of the eye-piece and the exit pupil of the objective. If we assume that the exit pupil of the system is in the focal plane of the eye-piece, the exit pupil position before the eye-piece is $l_{ep} = \infty$. This position is the exit pupil position for the collective lens $l_{ep} = l'_c = \infty$.

If the aperture stop is at the primary mirror, the exit pupil after the mirror objective can be calculated from the expression:

$$\frac{1}{l'_M} = \frac{2}{R_2} + \frac{1}{d}.$$

Here l'_M is the exit pupil position for the objective with respect to the secondary mirror, R_2 is the radius of the second mirror, d is the distance between the mirrors.

The entrance pupil position for a collective lens is:

$$l_c = l'_M - S'_{F'_{ob}}$$

Thus, the focal length of the collective lens can be found as follows:

$$f'_c = \frac{l'_c \cdot l_c}{l_c - l'_c}$$

A collective lens can usually have a simple plano-convex shape, the thickness can be chosen as $D_c/4 \ldots D_c/5$, where D_c is the diameter of the collective lens:

$$D_c = 2 f'_{ob} \tan\omega .$$

The radius of the convex surface is:

$R_c = f'_c\,(n-1)$,

n is the refraction index of the material.

Insert the collective lens into the system.

12. If necessary, optimize the image quality in the system keeping the necessary first-order properties. Save for the report and insert the information about the final Lens Data and the aberrations of the final system.

A telescope system with a lens inverting system

A basic layout of the system with a lens inverting system is presented in Figure 5. In the design below we assume that the lens inverting system (the relay system) has a unit magnification $V = -1$.

1. Calculate the first-order properties for the system and its components: find the focal lengths of the components, the angular fields, the exit pupil and other characteristics using following formulas.

Magnification of the system:

$$\Gamma = -\frac{f'_{ob}}{f'_{ep}} V_{LIS} .$$

The magnification of the inverting system is given as $V_{LIS} = -1$.

Angular field of view in the object space:

$$\tan\omega = \tan\omega' / \Gamma .$$

Focal length of the objective:

$$f'_{ob} = D \cdot F\# .$$

Focal length of the eye-piece:

$$f'_{ep} = f'_{ob} / \Gamma .$$

Exit pupil diameter:

$$D' = D / \Gamma$$

F-number of the eye-piece:

$$F\#_{ep} = f'_{ep} / D'$$

We assume here that the objective is a cemented doublet. Below, we consider the design features of this system type.

Thus, the telescope objective has characteristics as follows:

1. Focal length f'_{ob}=_____;
2. Entrance pupil diameter $D_{ob}=D$=_____;
3. Angular field of view $2\omega_{ob}=2\omega$=_____;

The telescope reversed eye-piece is to have the following characteristics:

1. Focal length f'_{ep}=_____;
2. F-number of the eyepiece $F\#_{ep}$=_____;
3. Angular field of view $2\omega_{ep}=2\omega'$=_____;

2. Assuming that all the components are to be inside the tube with the maximum diameter D_0, calculate the main characteristics of the other components of the system – the focal length of the components of the lens inverting system, and distance between the components. At this stage, the collective lens can also be calculated.

To find the required focal length for the lens inverting system, first, calculate the maximum tube diameter:

$$D_0 = 2f'_{ob}\tan\omega \; .$$

The focal length of the first component of the inverting lens system is:

$$f'_{LIS1} = f'_3 = \frac{D_0}{D} f'_{ob} \; .$$

If $V_{LIS} = -1$, the second component of the inverting system has the focal length equal to the focal length of the first component:

$$f'_3 = f'_4$$

The distance between the components of the inverting system for the vignetting 50% is:

$$d = f'_3 = f'_4$$

Calculate the focal length of the collective lens as described in the theoretical section (see expressions (26) – (33)), or as shown in Figure 7 and in the corresponding formulas. Here we repeat the second option as follows:

- For the given or chosen entrance pupils position l_p calculate the exit pupil position after the objective:

$$l'_{p1} = \frac{f'_{ob}\, l_p}{l_p + f'_{ob}}$$

- If the aperture stop is on the objective, $l_p = 0$ and $l'_{p1} = f'_{ob}$. The entrance pupil position for the collective lens is $l_{p2} = l'_{p1} - f'_{ob}$.
- The exit pupil position for the collective lens is $l'_{p2} = d_3/2$
- Thus, the focal length of the collective lens is:

$$f'_2 = \frac{l'_2 l_2}{l_2 - l'_2}$$

To check the calculations, compose the whole system using paraxial lenses in Zemax Optic Studio. Check the angular magnification, the pupil positions, and the layout.

3. The next stage is to choose and design the real lens components, initially, without a lens inverting system.

According to the characteristics of the eye-piece choose it from the catalog:

- The focal length of the eye-pieces selected from the catalog f'_{cat} is not to be more than twice as large or half as small as the necessary focal length f'_{ep}. If the focal length chosen is too small compared to the necessary value, after scaling to the necessary focal length it may lead to a large amount of aberrations that may be difficult to correct. If the focal length is too large compared to the necessary value, after scaling it may result in a undesirably small thicknesses or too small radii;
- F#cat is to be smaller than $F\#_{ep}$: it guarantees that after scaling the pupil diameter of the eye-piece will not smaller than the required value;
- $2\omega_{cat}$ is to be larger than $2\omega_{ep}$.

The characteristics of the eye-piece from the catalog:

Focal length f'_{cat} =_____;
F-number of the eye-piece $F\#_{cat}$=_____;
Angular field of view $2\omega_{cat}$=_____;

4. Set the eye-piece in Zemax Optic Studio software. Use at least three wavelengths (λ_e = 0.545 μm, $\lambda_{F'}$ = 0.643 μm, $\lambda_{F'}$ = 0.480 μm). Analyze the first-order properties, the layout, the spot diagrams and the aberration plots.

Lens Data of the eye-piece from the catalog:

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
1				
2				
3				
…				
N				

Cardinal points of the eye-piece from the catalog

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm

5. **5.** Using the instrument "***Make Focal***" from the menu of LDE scale the system to have the necessary focal length.
6. **6.** Correct the aperture and the field of view: set the values according to the calculations and the assignment.

Lens Data of the eye-piece (reversed ray path: the object is in infinity)

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
1				
2				
3				
…				
N				

Cardinal points of the eye-piece

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm

Save for the report:
Figure 1 – Layout
Figure 2 – Spot diagrams
Figure 3 – Ray fan aberration
Figure 4 – Field Curvature / Distortion

7. **7.** Analyze the image quality of the eye-piece (see p. 6 in Section "*A telescope system with a mirror objective*")

8. **8.** Calculate the first-order properties and perform the aberration correction of the cemented doublet objective.

In figure 16, a cemented doublet is shown schematically, below, pairs of glasses are given for the design of the system

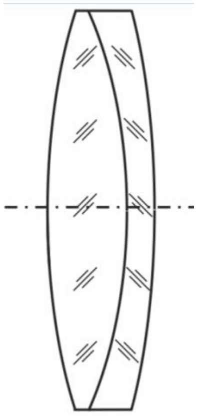


Figure 16 – Cemented doublet schematic drawing

Glass combinations:

F2 – N-FK5	SF6–N-K5	F2 – LAK11
SF66 – N-K5	N-SF4–N-K5	LF5– LAK11
N-SF6 – N-K5	N-SF5–N-K5	N-SF4–LAK11
F2 – N-K5	LF5–N-FK5	F4 – LAK11
SF1 – N-K5	F2–N-FK5	SF15–LAK11
SF2 – N-K5	F4– N-FK5	F2–N-LAK35
SF10 – N-K5	F2 – FK3	SF53 – BK7
SF53 – N-K5	SF10– BK7	F2 –N-SK5
N-F2 – N-K5	SF15 – N-K5	N-K5 – N-SF6

Calculate the optical powers of the lenses, so that they meet the achromatic condition and the power condition:

$$\begin{cases} \varphi_1 + \varphi_2 = 1 \\ \dfrac{\varphi_1}{\nu_1} + \dfrac{\varphi_2}{\nu_2} = 0 \end{cases}$$

Here, in the equations, the optical power of the cemented system is assumed to be 1, thus, all the values will be in the scale of the focal length or relative to the total optical power. Hence, the optical power of the lenses from the system above can be found:

$$\varphi_1 = \frac{\nu_1}{\nu_1 - \nu_2}, \quad \varphi_2 = -\frac{\nu_2}{\nu_1 - \nu_2},$$

where ν_1, ν_2 are the dispersion coefficients for the first and the second glass:

$$\nu = \frac{n_e - 1}{n_{F'} - n_{C'}}$$

At the stage of preliminary design we can assume a very small thickness of the lenses and hence, can neglect it, so the optical power of the lenses can be described as:

$$\varphi_1 = (n_{e1} - 1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

$$\varphi_2 = (n_{e2} - 1)\left(\frac{1}{r_2} - \frac{1}{r_3}\right)$$

For the preliminary design we can use additional constraints for more convenient calculations, thus, we can choose one of the additional constraints

1) r_1 or r_3 is infinity: either the first or the last surface is plane;
2) $r_2 = -r_3$ symmetrical second lens;
3) $r_1 = -r_2$ symmetrical first lens.

All calculations up to this point were done for the total power of the system φ = 1. To find the radii in real units – in mm, it is necessary to multiply the values by the focal length of the objective:

$$R_1 = r_1 \cdot f'_{ob}$$

$$R_2 = r_2 \cdot f'_{ob}$$

$$R_3 = r_3 \cdot f'_{ob}$$

Choose the thickness of the lenses: for the positive lens, choose the thickness of about D/4...D/5, for the negative lens D/6…D/8. **Round to the value of thickness of one decimal digit maximum.**

9. Set the objective in Zemax Optic Studio software. Analyze the first-order properties, the layout, the spot diagrams and the aberration plots.

Optimize the objective using the radii as variable parameters. Correct the spherical aberration, the coma, the chromatic aberration (axial color), and control the focal length.

Lens Data of the objective

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
1				
2				
3				
…				
N				

Cardinal points of the objective

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm

Save for the report:
Figure 1 – Layout
Figure 2 – Spot diagrams
Figure 3 – Ray fan aberration
Figure 4 – Field Curvature / Distortion

10. Analyze the image quality of the objective.

11. Compose the system of the objective and the eye-piece, evaluate the image quality

In the system, the eye-piece is to be reversed to operate in a position where the parallel ray paths are after the eye-piece.
Calculate the distance between the lenses of the objective and the eye-piece:
$t = S'_{F'ob} + \overleftarrow{S}'_{F'ep}$.

Here $\overleftarrow{S}'_{F'ep}$ is the back focal length of the eye-piece in a reversed ray path (see the Table above for the eye-piece)

Lens Data of the system

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
1				
2				
3				
…				
N				

Check the main characteristics of the composed system: the focal length is to be near infinite. Check the layout of the system.
In System Explorer in Aperture settings tick "*Afocal image space*" to analyze the aberrations in angular units (transverse aberrations) and in diopters (longitudinal aberrations).

Save for the report:
General characteristics:
Angular magnification
Entrance pupil diameter

Exit pupil diameter
Entrance pupil position (with respect to the first lens)
Exit pupil position (with respect to the last lens)
Angular field in the object space
Angular field in the image space

12. Design the lens inverting system: it contains two cemented components, placed symmetrically relative to the aperture stop.

The focal lengths of the symmetric lens inverting systems were calculated in p. 2. A schematic drawing of a lens inverting system is presented in Figure 17.

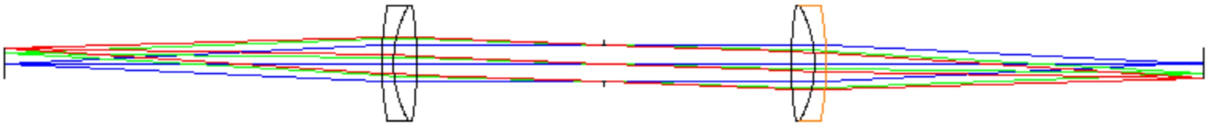


Figure 17 – Symmetrical lens inverting system

To design it in real lenses, it is necessary to find the angular field of the component and its f-number.

The focal length of the component of the lens inverting system for a symmetrical system with a unit magnification is as follows:

$$f_3' = f_4' = \frac{D_0}{D} f_{ob}'$$

F-number of second doublet of reversing lens system is: f'_3 / D_0

The angular field of view of the second doublet of a reversing lens system is:

$$2\omega = 2\arctan\left(\frac{D_0}{2f'_{LIS\,2}}\right)$$

The object height for an inverting lens system is:

$$y = 2f'_{ob}\tan\omega$$

Calculate the doublet lens as described in step **6** for the objective design: choose glasses, calculate the preliminary radii of lenses and choose the thickness. When designing the second half of the lens inverting system set the aperture stop in front of the component at the distance $d_{AS} = f'_3/2$.

Correct the astigmatism, the spherical aberration and the axial color using the radii as variables, and keep the focal length.

Lens Data of the second doublet of a reversing lens system

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
1				
2				
3				

Cardinal points of the second doublet of a lens inverting system

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm

Cardinal points of the first doublet of a lens inverting system

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm

Compose the two halves of the lens inverting system together. The distance between the lenses $d_{1\text{–}2} = f'_3$.

Check the first-order properties and the correction of aberrations.

Save for the report:

Figure 1 – Layout

Figure 2 – System Data

13. Compose the whole system together: insert the lens inverting system into the system consisting of the objective and the eye-piece.

The distance between the objective and the first doublet of a lens inverting system is:

$$d_{ob-1} = S'_{ob} - S_{F1}$$

The distance between the second doublet of a reversing lens system and the eye-piece:

$$d_{2-ep} = S'_{F2} - S_{Fep}$$

Add the collective lens to the system:

The convex surface of the telescope faces the objective, and as it is located in the intermediate image plane, the distance from the objective to the collective lens is:

$$d_{ob-col} = S'_{F'ob}$$

The distance from the collective lens to the inverting system is:

$$d_{col} = S_{H\,col} - S_F$$

Lens Data of the telescope system

№	Radii	Thickness	Glasses	Indexes of refraction for the primary wavelength
1				
2				
3				
…				
n				

Check the layout, the angular magnification, the exit and the entrance pupil positions.

Save for the report:

Figure 1 – Layout
Figure 2 – Spot diagrams
Figure 3 – Optical Path Difference
Figure 4 – Field Curvature / Distortion

14. Analyze the image quality. Find the angular spot size for the axial beam and the maximum field.
15. Perform optimization if necessary.
16. Write the report including some brief comments on your design steps and the conclusions about the resulting system

A telescope system with a prism

1. Calculate the first-order properties for the system and its components: find the focal lengths of the components, their diameter, F-numbers, and other characteristics using following formulas.

Magnification of the system:

$$\Gamma = -\frac{f'_{ob}}{f'_{ep}}\beta_{prism}$$

Magnification of the prism inverting system $\beta_{prism} = -1$.

Angular field in the object space:

$$\tan\omega = \tan\omega_{ob} = \frac{\tan\omega}{\Gamma}$$

Focal length of the objective:

$$f'_{ob} = D \cdot F\#$$

Focal length of the eye-piece:

$$f'_{ep} = \frac{f'_{ob}}{\Gamma}$$

Exit pupil diameter:

$$D' = \frac{D}{\Gamma}$$

F-number of the eye-piece:

$$F\#_{ep} = \frac{f'_{ep}}{D'}$$

Similarly to the previously considered cases, here we assume that the objective is a cemented doublet system. According to the calculation results above, it has the following characteristics:

1. Focal length f'_{ob}=_____;
2. Entrance pupil diameter $D_{ob}=D$=_____;
3. Angular field of view $2\omega_{ob}=2\omega$=_____;

The telescope reversed eye-piece is to have the characteristics as follows:

1. Focal length f'_{ep}=_____;
2. F-number of the eyepiece $F\#_{ep}$=_____;
3. Angular field of view $2\omega_{ep}=2\omega'$=_____;

2. According to the characteristics of the eye-piece, choose it from the catalog:

- The focal length of the eye-pieces selected from the catalog f'_{cat} is not to be more than twice as large or half as small as the necessary focal length f'_{ep}. If the focal length chosen is too small compared to the necessary value, after scaling to the necessary focal length it may lead to a large amount of aberrations that may be difficult to correct. If the focal length is too large compared to the necessary value, after scaling it may result in a undesirably small thicknesses or too small radii;

- $F\#_{cat}$ is to be smaller than $F\#_{ep}$: it guarantees that after scaling, the pupil diameter of the eye-piece will not be smaller than the required value;
- $2\omega_{cat}$ is to be larger than $2\omega_{ep}$.

The characteristics of the eye-piece from the catalog:

1. Focal length f'_{cat}=_____;
2. F-number of the eye-piece $F/\#_{cat}$=_____;
3. Angular field of view $2\omega_{cat}$=_____;

3. Set the eye-piece in Zemax Optic Studio software. Use at least three wavelengths (λ_e = 0.545 µm, $\lambda_{C'}$ = 0.643 µm, $\lambda_{F'}$ = 0.480 µm). Analyze the first-order properties, the layout, the spot diagrams and the aberration plots.

Lens Data of the eye-piece from the catalog

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
1				
2				
3				
…				
N				

Cardinal points of the eye-piece from the catalog:

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm

4. Using the instrument “***Make Focal***” from the menu of LDE scale the system to have the necessary focal length

5. Correct the aperture and the field of view: set the values according to the calculations and the individual assignment.

Lens Data of the eye-piece (reversed ray path: object is in infinity)

№	Radii	Thickness	Glasses	Indexes of refraction for the primary wavelength
1				
2				
3				
…				
N				

Cardinal points of the eye-piece

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm

Save for the report:
Figure 1 – Layout
Figure 2 – Spot diagrams
Figure 3 – Ray fan aberration
Figure 4 – Field Curvature / Distortion

6. Analyze the image quality of the eye-piece (see p. 6 in Section "*A telescope system with a mirror objective*")

7. Calculate the first-order properties and perform the aberration correction of the cemented doublet objective.

In the Figure below, a cemented doublet is shown schematically, below, pairs of glasses are given for the design of the system

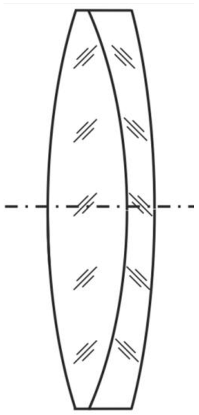


Figure 18 – Cemented doublet schematic drawing

Glass combinations:

F2 – N-FK5	SF6–N-K5	F2 – LAK11
SF66 – N-K5	N-SF4–N-K5	LF5– LAK11
N-SF6 – N-K5	N-SF5–N-K5	N-SF4–LAK11
F2 – N-K5	LF5–N-FK5	F4 – LAK11
SF1 – N-K5	F2–N-FK5	SF15–LAK11
SF2 – N-K5	F4– N-FK5	F2–N-LAK35
SF10 – N-K5	F2 – FK3	SF53 – BK7
SF53 – N-K5	SF10– BK7	F2 –N-SK5
N-F2 – N-K5	SF15 – N-K5	N-K5 – N-SF6

Calculate the optical powers of the lenses, so that they meet the achromatic condition and the power condition:

$$\begin{cases} \varphi_1 + \varphi_2 = 1 \\ \dfrac{\varphi_1}{\nu_1} + \dfrac{\varphi_2}{\nu_2} = 0 \end{cases}$$

Here in the equations, the optical power of the cemented system is assumed to be 1, thus, all the values will be in the scale of the focal length or related to the total optical power. Hence, the optical power of the lenses from the system above can be found:

$$\varphi_1 = \frac{\nu_1}{\nu_1 - \nu_2}, \quad \varphi_2 = -\frac{\nu_2}{\nu_1 - \nu_2},$$

where ν_1, ν_2 are the dispersion coefficients for the first and the second glass:

$$\nu = \frac{n_e - 1}{n_{F'} - n_{C'}}$$

At the stage of preliminary design we can assume a very small thickness of the lenses and hence, can neglect it, so the optical power of the lenses can be described as:

$$\varphi_1 = (n_{e1} - 1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

$$\varphi_2 = (n_{e2} - 1)\left(\frac{1}{r_2} - \frac{1}{r_3}\right)$$

For a preliminary design we can use additional constraints for more convenient calculations, thus, we can choose one of the additional constraints

4) r_1 or r_3 is infinity: either the first or the last surface is plane;
5) $r_2 = -r_3$ symmetrical second lens
6) $r_1 = -r_2$ symmetrical first lens

All calculations up to this point were done for the total power of the system φ = 1, to find the radii in real units – in mm, it is necessary to multiply the values by the focal length of the objective:

$$R_1 = r_1 \cdot f'_{ob}$$

$$R_2 = r_2 \cdot f'_{ob}$$

$$R_3 = r_3 \cdot f'_{ob}$$

Choose the thickness of the lenses: for the positive lens, choose the thickness of about D/4...D/5, for the negative lens D/6…D/8. Round the value to one decimal digit maximum.

8. Set the objective in Zemax Optic Studio software. Analyze the first-order properties, the layout, the spot diagrams and the aberration plots.

Optimize the objective using the radii as variable parameters. Correct the spherical aberration, the coma, the chromatic aberration (axial color) and control the focal length.

Lens Data of the objective

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
1				
2				
3				
…				
N				

Cardinal points of the objective

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm

Save for the report:
Figure 1 – Layout
Figure 2 – Spot diagrams
Figure 3 – Ray fan aberration
Figure 4 – Field Curvature / Distortion

9. Analyze the image quality of the objective.
10. Compose the system of the objective and the eye-piece, evaluate the image quality.

In the system, the eye-piece is to be reversed to operate in a position where the parallel ray paths are after the eye-piece.
Calculate the distance between the lenses of the objective and the eye-piece:
$t = S'_{F'ob} + \overleftarrow{S}'_{F'ep}$.

Here $\overleftarrow{S}'_{F'ep}$ is the back focal length of the eye-piece in a reversed ray path (see the Table above for the eye-piece)

Lens Data of the system

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
1				
2				
3				
…				
N				

Check the main characteristics of the composed system: the focal length is to be near infinite. Check the layout of the system.

In System Explorer in Aperture settings tick “*Afocal image space*” to analyze the aberrations in angular units (transverse aberrations) and in diopters (longitudinal aberrations).

Save for the report:
General characteristics:
Angular magnification

Entrance pupil diameter
Exit pupil diameter
Entrance pupil position (with respect to the first lens)
Exit pupil position (with respect to the last lens)
Angular field in the object space
Angular field in the image space

11. Add the inverting system: Porro prism system.

In Figure 19, a layout is shown with a tunnel diagram for a prism illustrating the calculation of the distances between the prism and other components of the system. Calculate the distance z between the intermediate image (in Figure 19 it is on the second surface of the reticle):

$$z \geq f'^2_2$$

This condition corresponds to the situation when the exit surface of a prism is out of the accommodation range of the human eye, hence, the observer does not see any small scratches or digs on this surface.

The angle of the auxiliary ray traveling from the center of the exit surface of the prism can be calculated according to the formula:

$$\tan\gamma = \frac{n}{2k}$$

Here n is the refraction index of prism material, k is the prism coefficient, the ratio between the path length inside the prism and the working beam diameter. For Porro system $k = 4$.

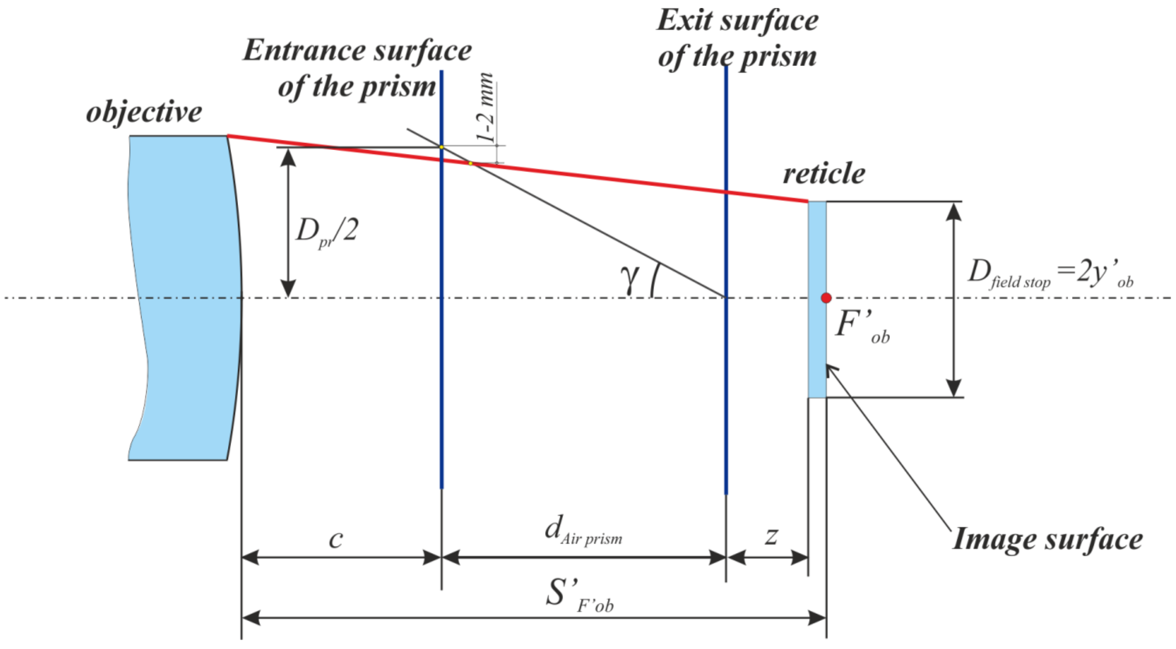


Figure 19 – Tunnel diagram for a prism calculation

If all linear and angular values are drawn in the appropriate scale, the working beam diameter on the entrance surface of the prism can be taken from the drawing. Thus, take the size $D_{pr}/2$ from the drawing.

Calculate the ray path length in the prism:

$$d_{prism} = k \cdot D_{pr}$$

The thickness of the equivalent air plate:

$$d_{Air\ prism} = \frac{d_{prism}}{n}$$

To check the calculation results, compare the value $d_{Air\ prism}$ to the value in the drawing.

Calculate the equivalent air thickness of the glass plate with etched lines and a grid on it – the reticle:

$$d_{Air\ reticle} = \frac{d_{reticle}}{n}$$

For the majority of options, $d_{reticle}$ =5 mm can be chosen.

Calculate the distance from the objective to the entrance surface of the prism:

$$C = S'_{F'ob} - d_{Air\ reticle} - z - d_{Air\ prism}$$

Insert the prism into the telescope system

Lens Data of the telescope system

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
1				
2				
3				
…				
N				

Save for the report:
Figure 1 – System Data
Figure 2 – Spot diagrams
Figure 3 –Optical Path Different
Figure 4 – Field Curvature / Distortion

Analyze the image quality.

12. Perform optimization (automated correction / automated design, if necessary)

13. To make the system more visually comprehensible, make a 3D model of the prism:

- Describe the Porro prism system using a polygonal object (or see the file *.pob included by default into the set of polygonal objects in Zemax). Use the appropriate scale of the polygonal object, so that the system corresponded to the calculation of the prism in the individual assignment.
- Insert the prism system into the telescope system, check the main characteristics. Save for the report the 3D Layout or the shaded model.

14. Write the report including some brief comments on the design steps and the conclusions about the resulting system

Initial data for individual variants

#	Angular magnification	Angular field in the image space	Entrance pupil diameter, mm	F-number of the objective
1	20	2ω' = 40°	100	F/6
2	20	2ω'= 35°	90	F/7
3	30	2ω' = 35°	100	F/8
4	35	2ω' = 30°	70	F/10
5	60	2ω' = 30°	180	F/15
6	7	2ω' = 60°	40	F/6
7	50	2ω' = 35°	250	F/12
8	8	2ω' = 50°	30	F/6
9	45	2ω' = 30°	120	F/11
10	10	2ω' = 60°	50	F/6
11	50	2ω' = 40°	125	F/10
12	6	2ω' = 50°	30	F/4
13	55	2ω' = 30°	220	F/14
14	12	2ω' = 60°	45	F/5
15	25	2ω' = 35°	80	F/9
16	50	2ω' = 35°	200	F/10
17	40	2ω' = 40°	80	F/10
18	30	2ω' = 30°	80	F/9
19	60	2ω' = 30°	200	F/12
20	9	2ω' = 50°	40	F/5
21	10	2ω' = 60°	35	F/6

Example of designing a telescope system with a mirror objective

ITMO University

Project report on

Design of Telescopic System with Mirror Objective

Student:______________

Prof.:________________

Changchun

20__

I. Initial Parameters and Ideal Structural Design

1.1 Initial Parameters and Calculation Process

1.2 Ideal Structural Design

II. Objective System Design

2.1 Objective Model Selection

2.2 Overall Dimensions Calculation

2.3 Optimization of the Objective

2.3.1 The Optimization of Spherical Aberration and Coma

2.3.2 The Optimization of Astigmatism

III. Eyepiece Selection

IV. Combination of Objective and Eyepiece

V. Tolerancing Analysis

5.1 Settings on Tolerance Editor

5.2 Set Up on Tolerancing

1. Initial Parameters and Design in Paraxial Components

1.1 Initial Parameters and Calculation Process

Table 1 Initial parameters

Angular magnification	Field of view in the image space	Entrance pupil diameter	F-number (objective)
50	$2\omega'$=40°	125 mm	10

Using the equations below, we can get the 3 main parameters of our system.

$$f'_{ob} = D \cdot F/\#_{ob};$$

$$f'_{oc} = -\frac{f'_{ob}}{\Gamma};\ tg\omega_{ob} = \frac{tg\omega'}{\Gamma_{ob}} = arctan \text{ arctan } (tg\omega_{ob});\ D' = D/|\Gamma|$$

$$F/\#_{oc} = f'_{oc}/D'$$

Calculation results:

Table 2 Parameters of the objective

Focal length	Entrance pupil diameter	Exit pupil diameter	Field of view in the object space
1250 mm	125 mm	2,5 mm	0,8342°

Table 3 Parameters of the eyepiece

Focal length	F-number	Field of view in the image space
25mm	10	40°

1.2 *Ideal Structural Design*

Set the entrance pupil diameter at 125mm in the general settings and turn on the afocal image space option. Set the maximum field at 0.4171° in the field data and choose the *F*, *d*, *C* wavelength band for our system.

Set the components in our system as paraxial components and set the distance between the objective and the eyepiece as $d = f'_{ob} + f'_{oc}$, then set the focal length of these two components.

Table 4 Ideal model of the designed telescope

Surface type		Thickness		Semi-diameter	Focal length
OBJ	-	Infinity		Infinity	
STO	Paraxial	1275		62.5	1250
2	Paraxial	25.5	C	10.532	25
IMA	-			1.25	

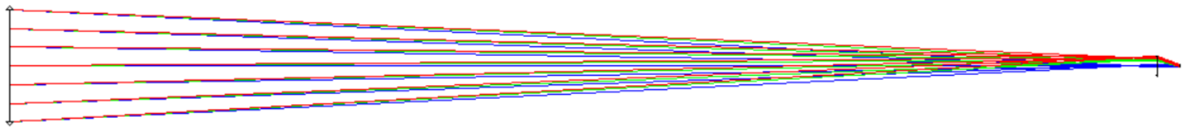


Figure 1 Ideal model of the designed telescope
(the last surface is the exit pupil surface)

2. Objective System Design

2.1 Objective Model Selection

As we can see in Table 1, both the focal length and the entrance pupil diameter of our objective are very large ($f'_{ob} > 1000mm, D > 100mm$), thus, our objective has to be a reflective system, so we choose the classic two-mirror system as our objective.

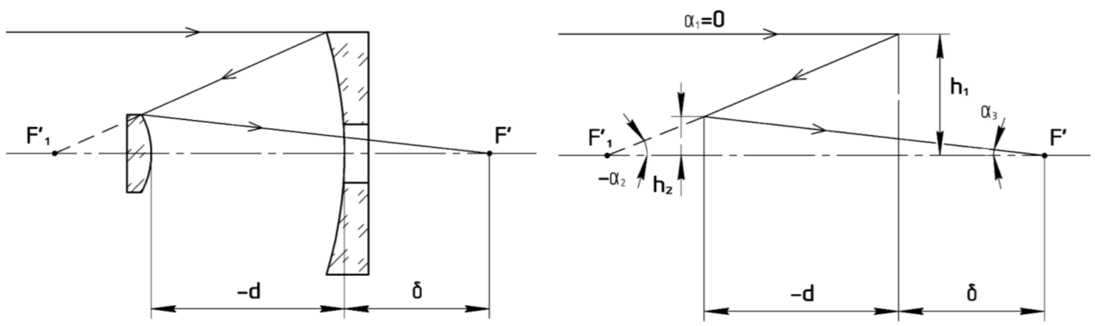


Figure 2 Basic model of a two-mirror system

2.2 Overall Dimensions Calculation

Set the obscuration ratio $\varepsilon = 0.35$, and $\delta = 0.05$. Using the equations below, we can get the parameters of the dimensions of my objective.

$$\alpha_1 = 0;\ \alpha_2 = \frac{\varepsilon - 1}{\varepsilon - \delta};\ \alpha_3 = 1\ ;\ \underline{d} = \delta - \varepsilon;\ h_1 = 1;\ h_2 = \varepsilon\ \cdot h_1;\ r_1 = \frac{2}{\alpha_2};$$

$$r_2 = \frac{2\varepsilon}{1 + \alpha_2}\ ;\ R_1 = r_1 \cdot f'_{ob}\ ;\ R_2 = r_2 \cdot f'_{ob};\ d = \underline{d} \cdot f'_{ob}$$

Calculation results:

Table 5 Dimensions of the objective

R_1/ mm (radius of the primary mirror)	R_2/ mm (radius of the secondary mirror)	d/ mm (distance between the mirrors)
-1153.846	-750.000	-375.000

Then introduce these parameters in ZEMAX. In “Surface 1 properties” choose the aperture type as “Circular Obscuration” and the maximum radius as the value of the third surface Semi-diameter. In “Surface 2 properties” choose the aperture type as “Circular Aperture”, the maximum radius as the value of the fist surface Semi-diameter. The minimum radius is the value of the third surface Semi-diameter.

Table 6 Preliminary Lens Data of the objective

Surf: type	Radius	Thickness		Glass	Semi-diameter	Conic
OBJ	Infinity	Infinity			Infinity	0
*	Infinity	375			67.960	0
*	-1153.846	-375		MIRROR	62.512	0
3	-750	437.5	M	MIRROR	24.582	0
IMA	Infinity	-			9.275	0

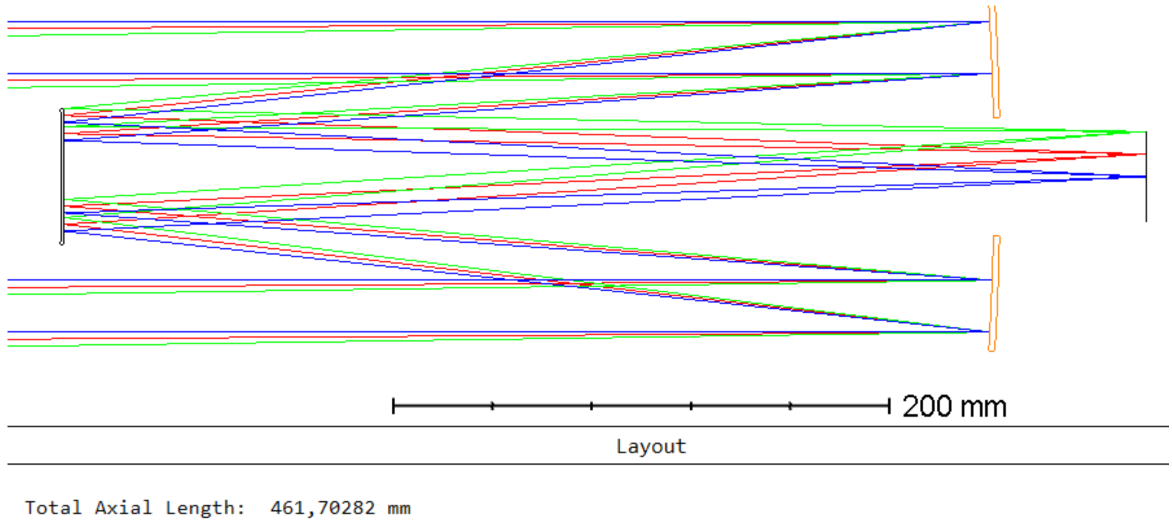


Figure 3 Layout of the objective (preliminary)

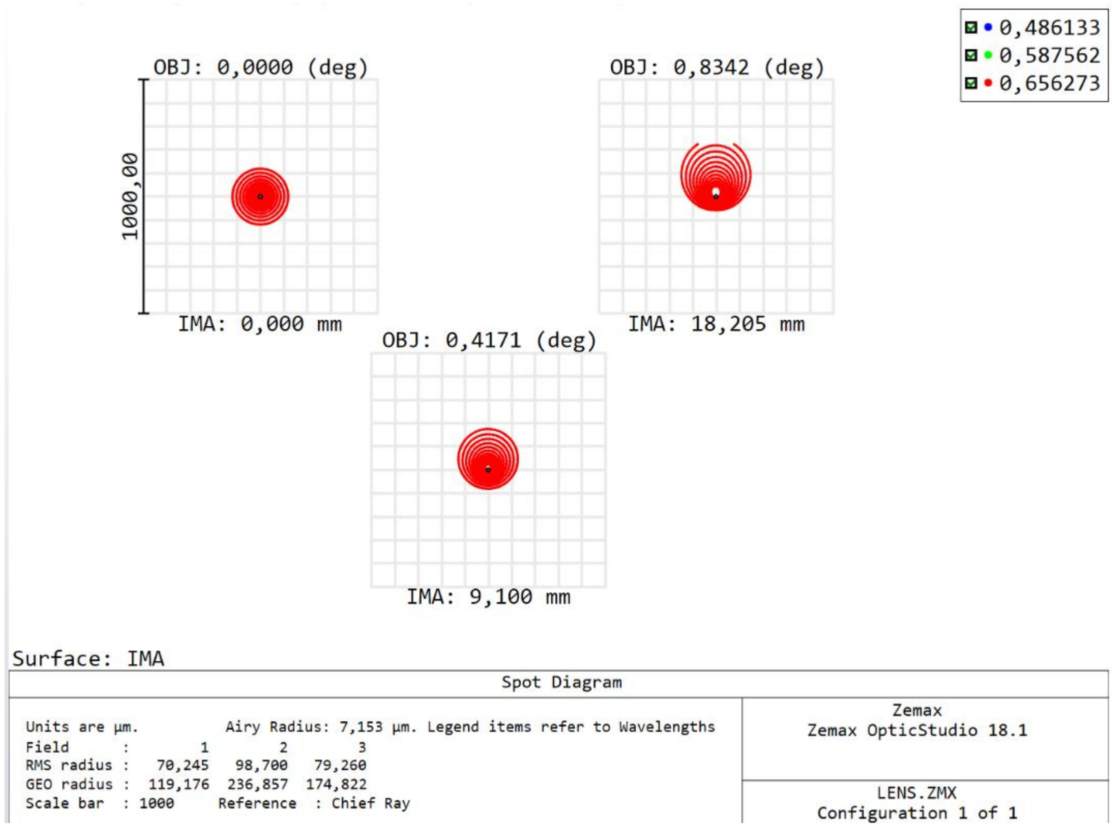


Figure 4 Spot Diagram of the objective (preliminary)

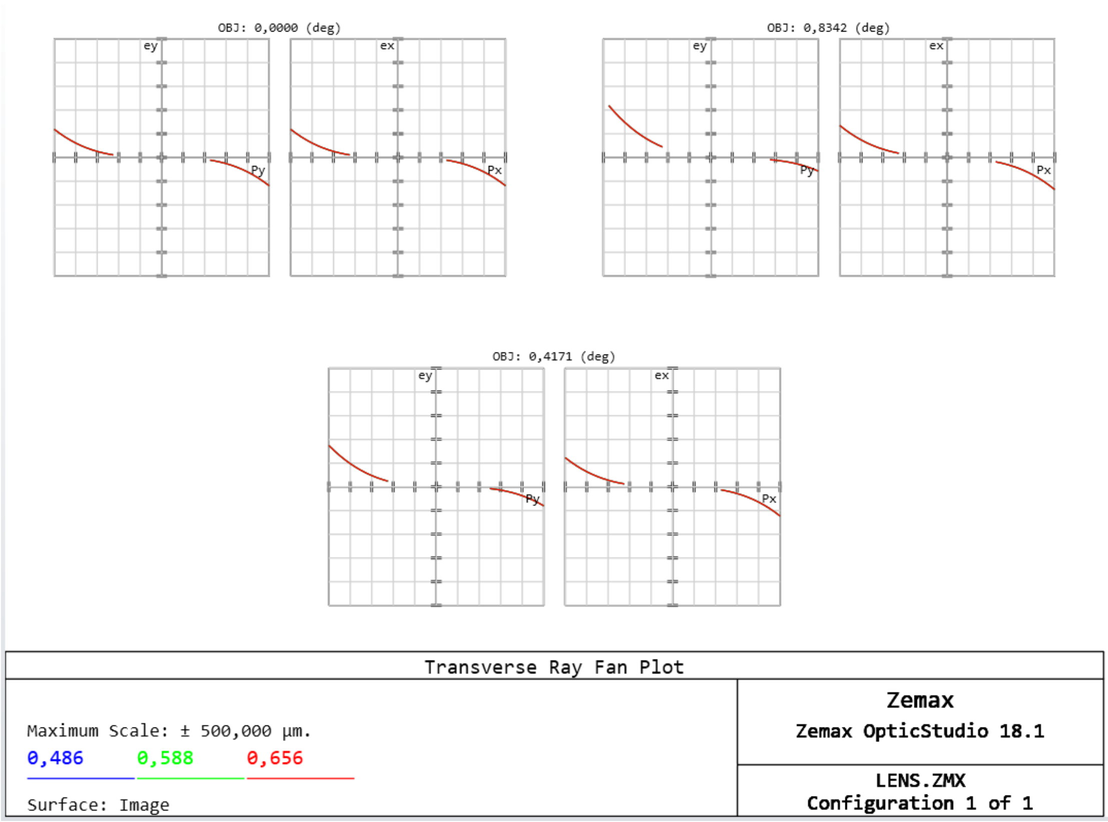


Figure 5 Ray Fan Plot of the objective (preliminary)

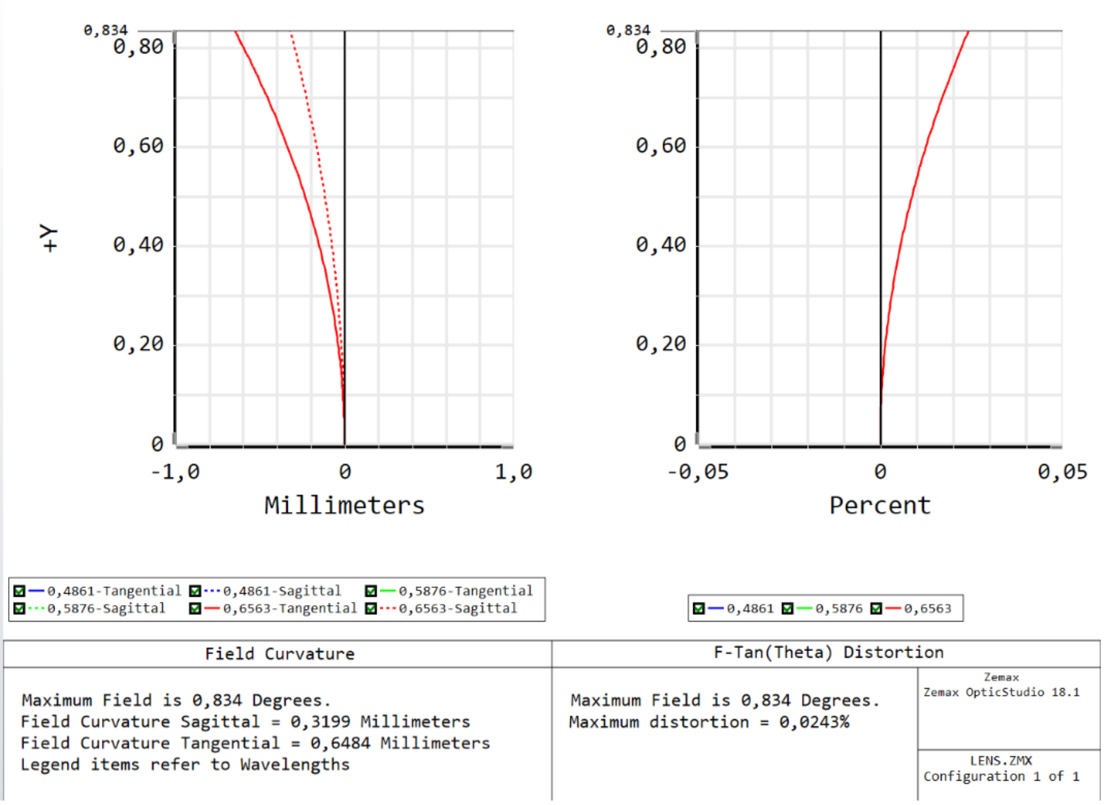


Figure 6 Field curvature/distortion of the objective (preliminary)

As we can see from the above Figures, there is clearly a large aberration in our current system, including the spherical aberration (mainly), and the coma (smaller compared with spherical aberration). The reason for this result is that we have used two spherical mirrors in our objective, so at the next step we will change our mirrors to aspherical ones.

2.3 Optimization of the objective

2.3.1 Optimization of the Spherical Aberration and the Coma

First, the operands in “Merit function” of ZEMAX, will be used to optimize the system.

Table 7 Merit Function (for the spherical aberration and the coma)

Operands	Additional settings	Target	Weight
COMA		0	1
OPDC	P_y=1	0	1

Table 8 Lens Data of the objective (first optimization)

Surf: type	Radius	Thickness		Glass	Semi-diameter	Conic	
OBJ	Infinity	Infinity			Infinity	0	
*	Infinity	375			67.960	0	
*	-1153.846	-375		MIRROR	62.512	-1.229	V
3	-750	437.5	M	MIRROR	24.582	-11.566	V
IMA	Infinity	-			9.275	0	

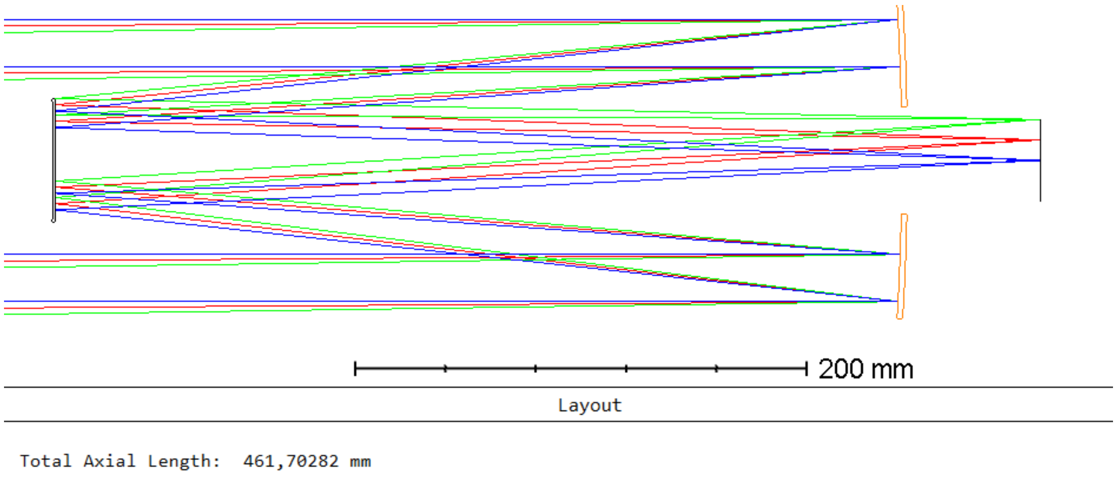


Figure 7 Layout of the objective (first optimization)

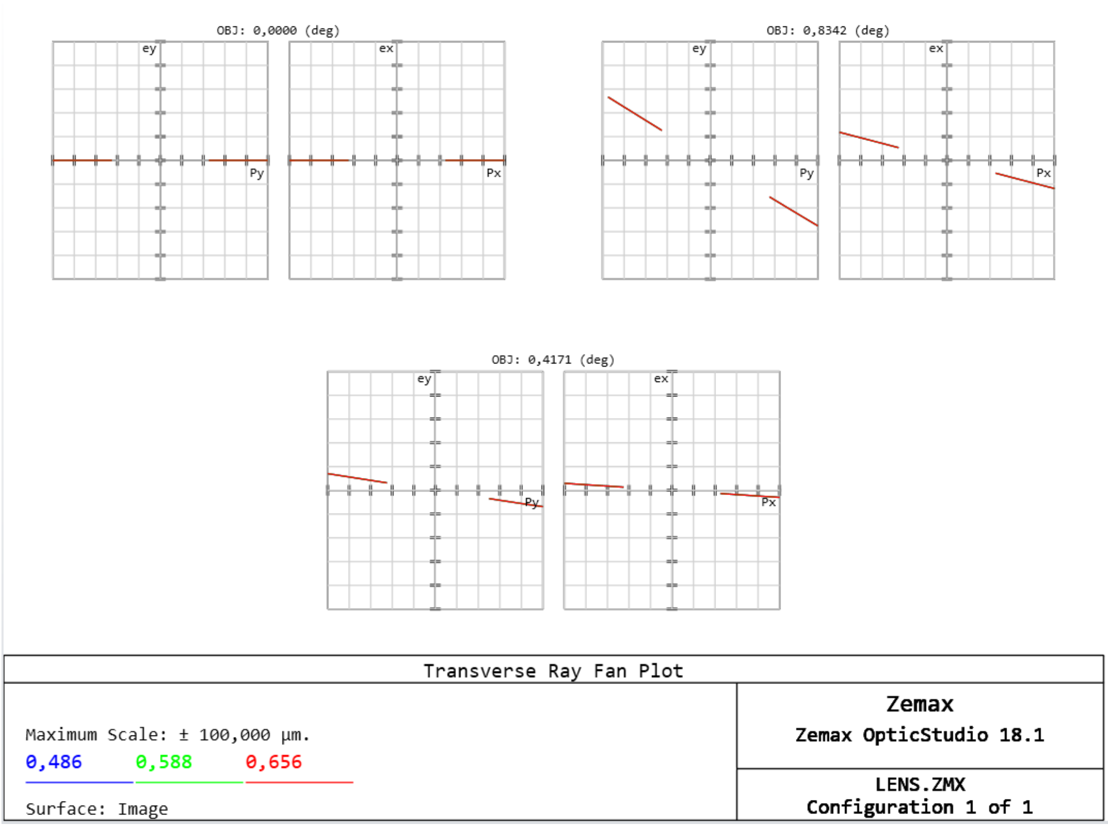


Figure 8 Spot Diagram of the objective (first optimization)

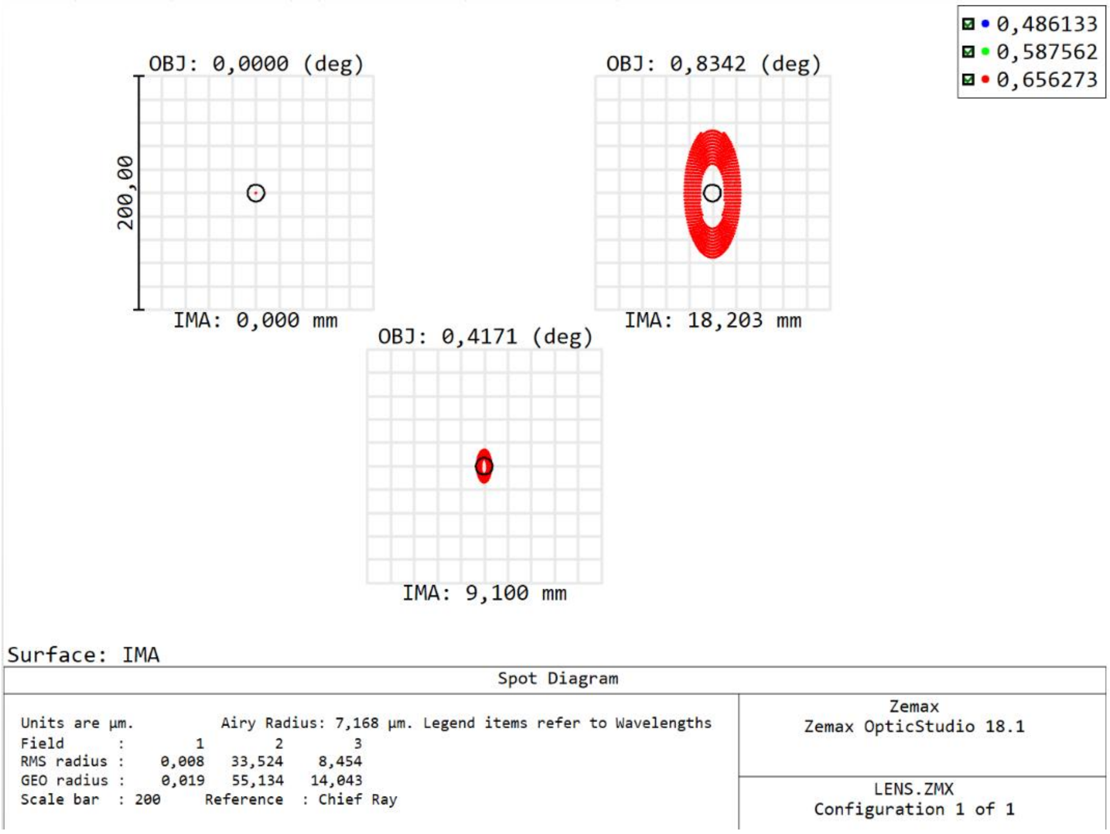


Figure 9 Ray Fan plot of the objective (first optimization)

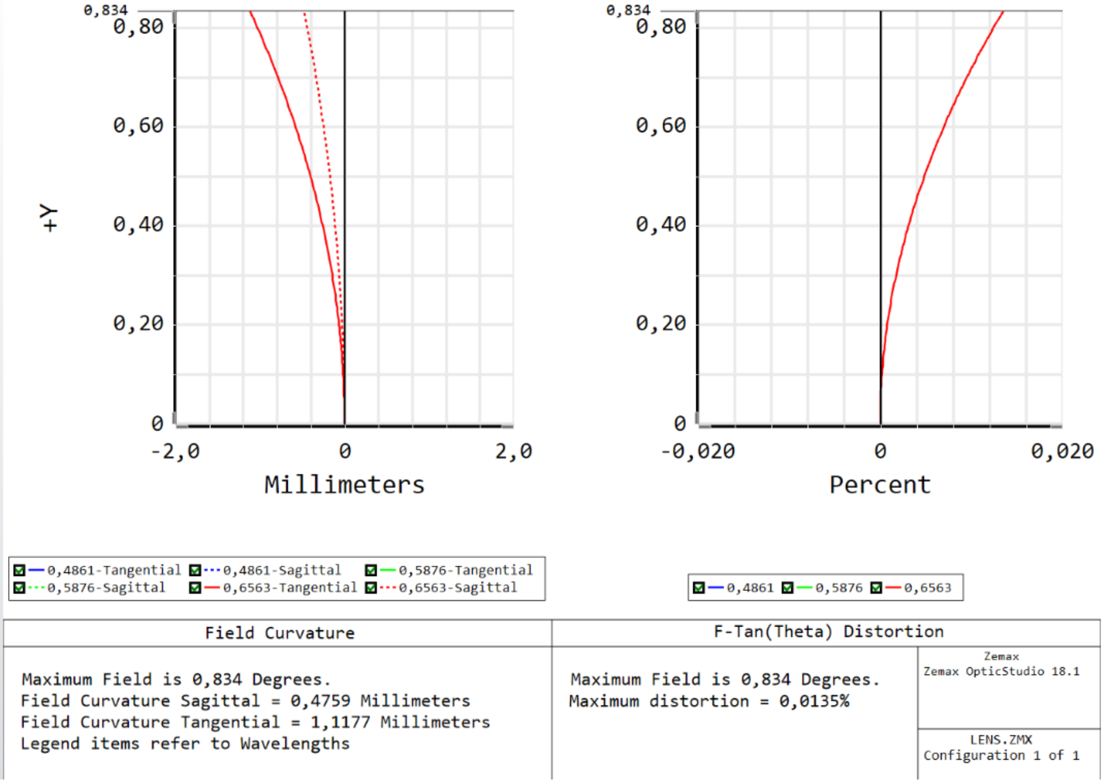


Figure 10 Field curvature/distortion of the objective (first optimization)

Now the two main types of aberration (the spherical aberration and the coma) are almost eliminated. The image quality has greatly improved, both the maximum scale of aberration and the radius of dispersion spots are much smaller compared to the previous system.

However, the curves in the transverse ray fan plot are almost straight, and the larger the field of view, the higher the value of the slope, which means that the defocus and the astigmatism exist in the current system, and the astigmatism increases synchronously with the field of view. So at the next step we will try to limit the astigmatism to further improve the image quality of our system.

Table 9 Cardinal points of the objective

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm
1249.999	2499.999	437,500	1249.999	-812,500

As we can see from the above Figures, there is still a little astigmatism in our system, however, the overall performance is much better, especially in the marginal region of the field. So it's time for us to design the eyepiece.

3. Eye-piece Selection

Choose the reversed eye-piece from the given catalogs. There are several limitations when selecting the eyepiece, namely:

(1) $f'_{ep}/2 < f'_{cat} < 2 \cdot f'_{ep}$;

(2)$F/\#_{cat} < F/\#_{ep}$;

(3) $2\omega_{ep} < 2\omega_{cat}$;

Based on the above limitations, we chose the "Eye-piece with a large eye relief" as the "better half" of my objective.

Table 10 Comparison between the catalog and calculated eye-pieces

Items	Calculated	Catalog eye-piece
Focal length	25 mm	25.065 mm
F-number	10	8.355
Field of view	40°	50°

Table 11 Lens Data of the reversed eye-piece from the catalog

#surface	Radii	Thickness	Glass	n	Diameter
				1.000000	
STO	Infinity	3.22		1.000000	1.5
1	0.000	7.00	CTK19	1.747647	34.20
2	-36.980	0.30		1.000000	35.44
3	65.770	3.20	TF10	1.813769	36.13
4	36.640	7.00	CTK19	1.747647	35.10
5	0.000	0.30		1.000000	34.67
6	29.240	14	CTK19	1.747647	33.04
7	-23.770	3.20	TF10	1.813769	30.66
8	23.770	7.61		1.000000	23.47
9	0.000			1.000000	22.56

Table 12 Cardinal points of the reversed eye-piece from the catalog

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm
25.10	3.22	0.04	28.33	25.14

“Make focal length” for this eyepiece, and change its entrance pupil diameter and the field of view in the general and the field settings, respectively.

Table 13 Lens Data of the reversed eye-piece

# surf	Radii	Thickness		Glass	n	Semi-Diameter
OBJ	Infinity	Infinity		-	1.000000	Infinity
STO	Infinity	3.343		-	1.000000	1.25
2	Infinity	6.970		LZ_CTK19	1.747647	16.987
3	-36.821	0.299			1.000000	17.644
4	65.487	3.186		LZ_TF10	1.813769	17.987
5	36.482	6.970		LZ_CTK19	1.747647	17.474
6	Infinity	0.299			1.000000	17.260
7	29.114	13.940		LZ_CTK19	1.747647	16.449
8	-23.668	3.186		LZ_TF10	1.813769	15.264
9	23.668	7.613	M	-	1.000000	11.684
IMA	0.000			-	1.000000	8.741

Table 14 Cardinal Points of the reversed eye-piece

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm
25.000	3.209	7,909	28.209	-17,091

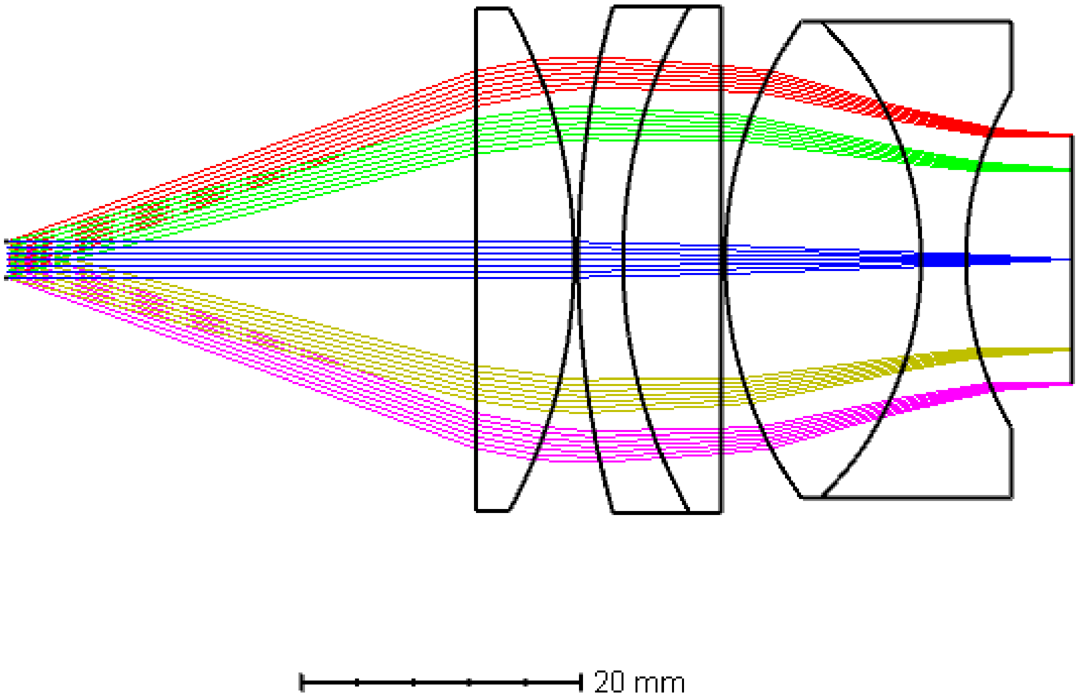


Figure 11 Layout of the reversed eye-piece

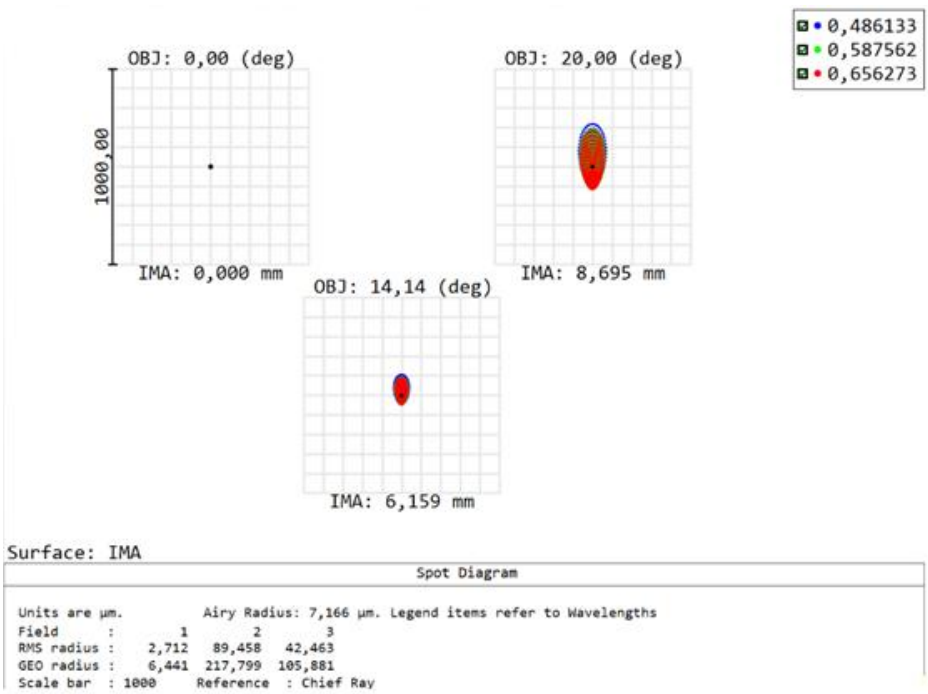


Figure 12 Spot Diagram of the reversed eye-piece

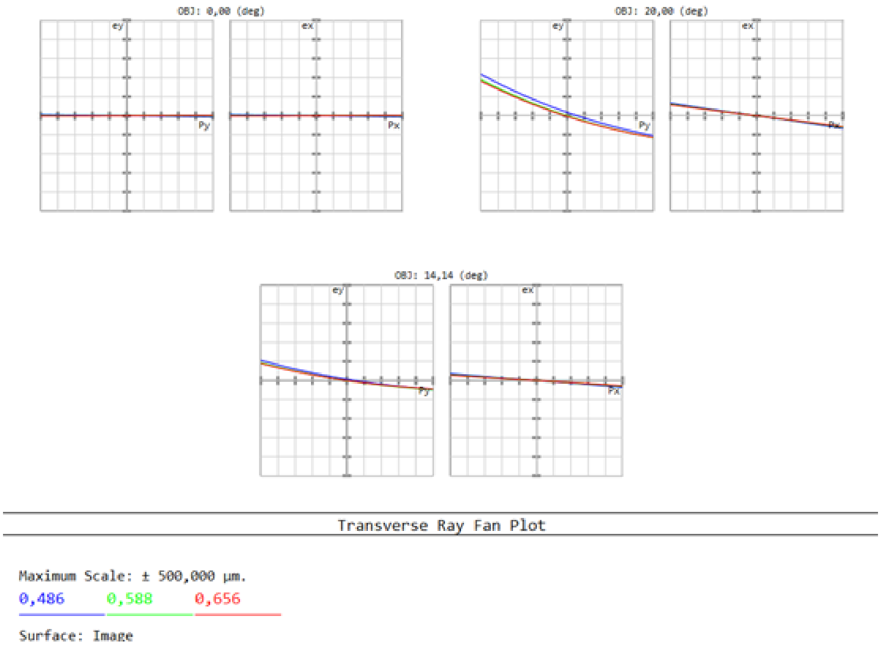


Figure 13 Ray Fan Plot of the reversed eye-piece

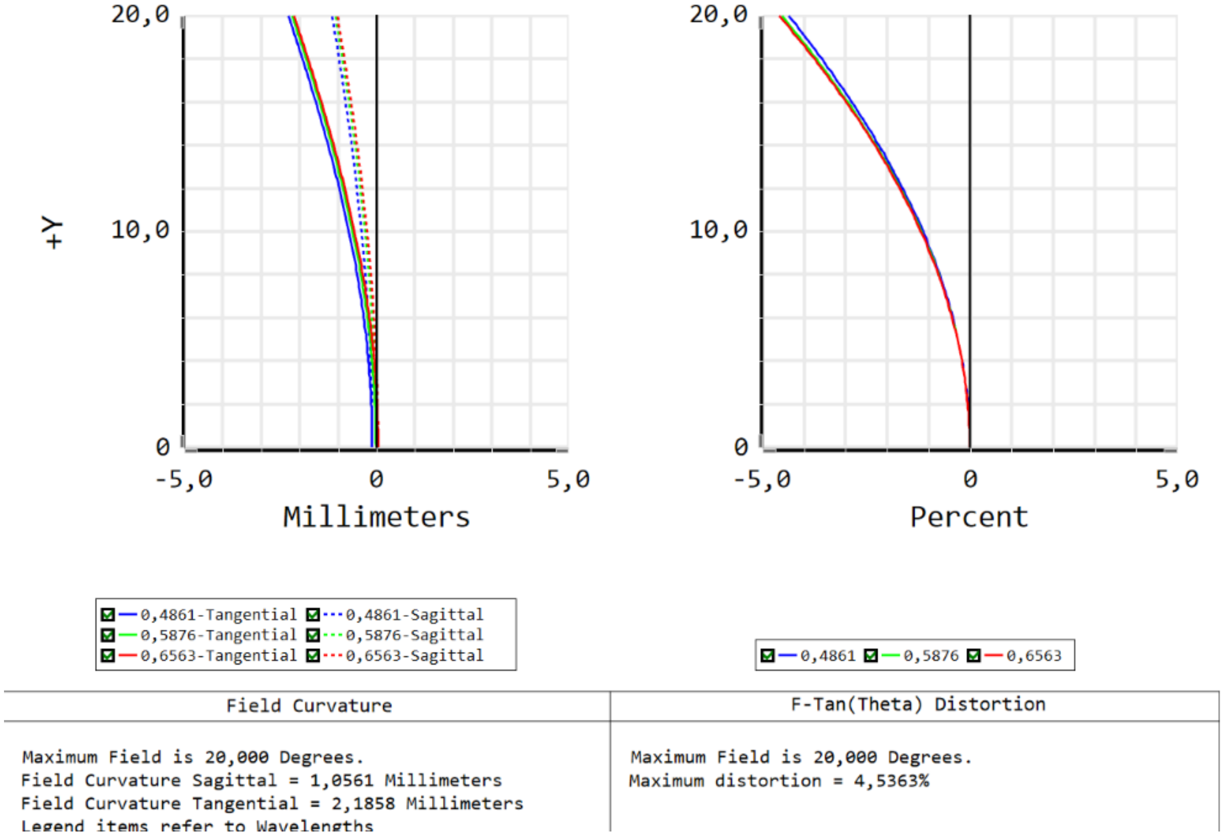


Figure 14 Field curvature/distortion of the reversed eye-piece

As we can see from the three Figures above, this eye-piece system can give an effective limitation on the spherical aberration and can produce high image quality in the paraxial region.

However, this system has serious coma, the astigmatism, and the off-axis lateral chromatic aberration, these severe aberrations exist almost everywhere except for the paraxial region, and this may result in low image quality.

3. Combination of the Objective and the Eyepiece

Now that we have finished the selection, modification and design of the objective and the eyepiece, what do we do now to compose these two components and turn the whole system into an afocal telescopic system?

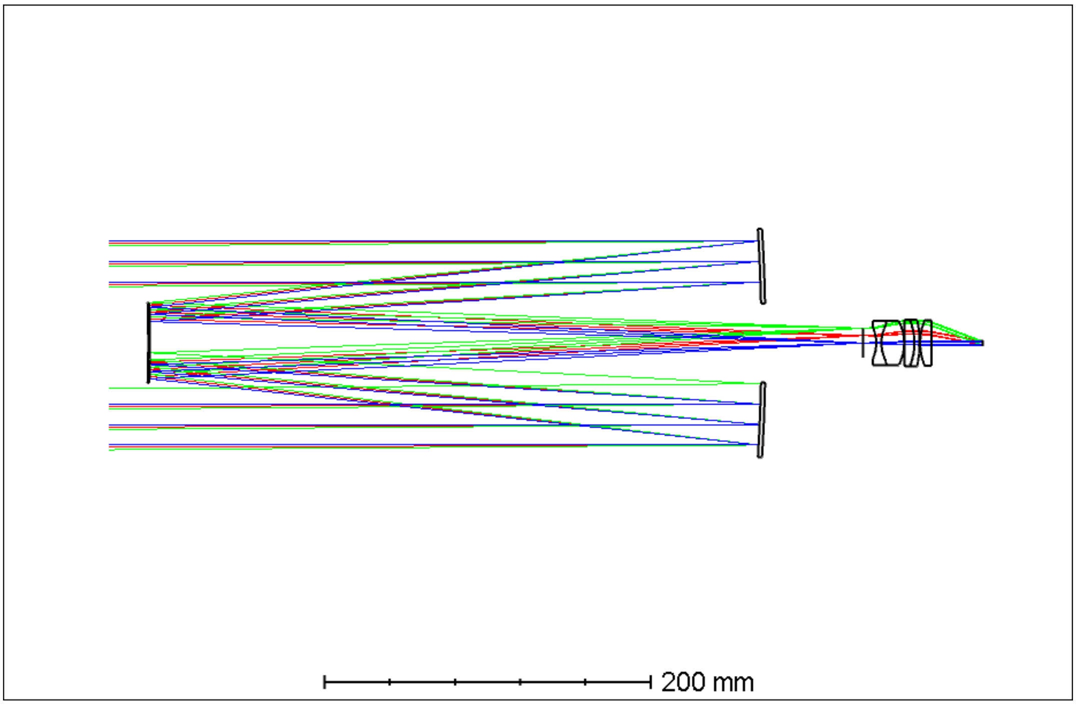


Figure 15Layout of the whole system
(the last surface is the exit pupil surface)

Table 15 Lens Data of the whole system

#surf	Radii	Thickness		Glass	n	Semi-Diameter	Conic
OBJ	Infinity	Infinity		-	1.000	Infinity	
STO	-1153.846	-375.00		MIRROR	-	62.512	-1.229
2	-750.000	437.30		MIRROR	-	24.655	-11.566
3	Infinity	7.943	V	-	1.000	9.101	
4	-23.668	3.19		LZ_TF10	1.814	9.494	
5	-23.668	13.94		LZ_CTK19	1.748	11.349	
6	29.114	0.30			1.000	13.44	
7	Infinity	6		LZ_CTK19	1.748	13.777	
8	36.482	3,186		LZ_TF10	1.814	13.95	
9	-65,487	0.30		-	1.000	14.247	
10	36,821	6.97		LZ_CTK19	1.748	13.967	
11	Infinity	31.22	C	-	1.000	13.094	
IMA	Infinity			-	1.000		

Table 16 Merit Function (for the whole system)

Operands	Additional settings	Target	Weight
RANG	$P_y=1$	0	1
COMA	-	0	1
OPDC	$P_y=1$	0	1

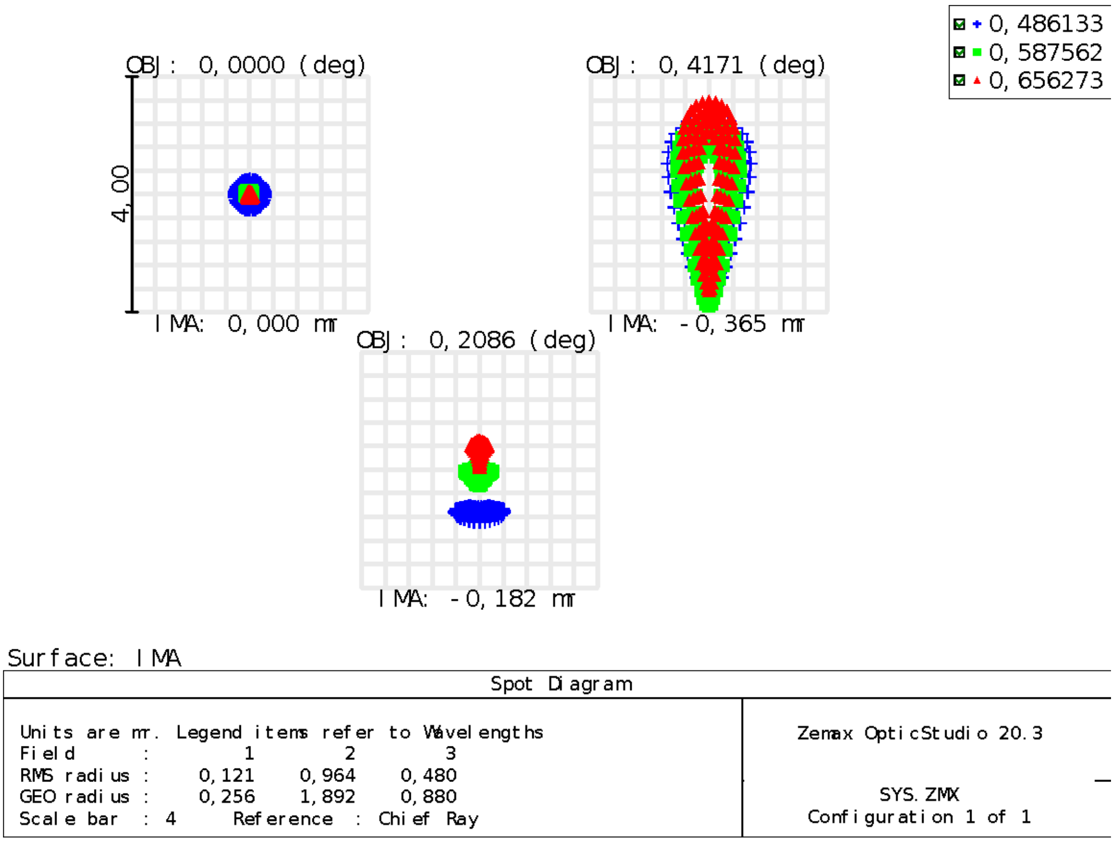


Figure 16 Spot Diagram of the whole system

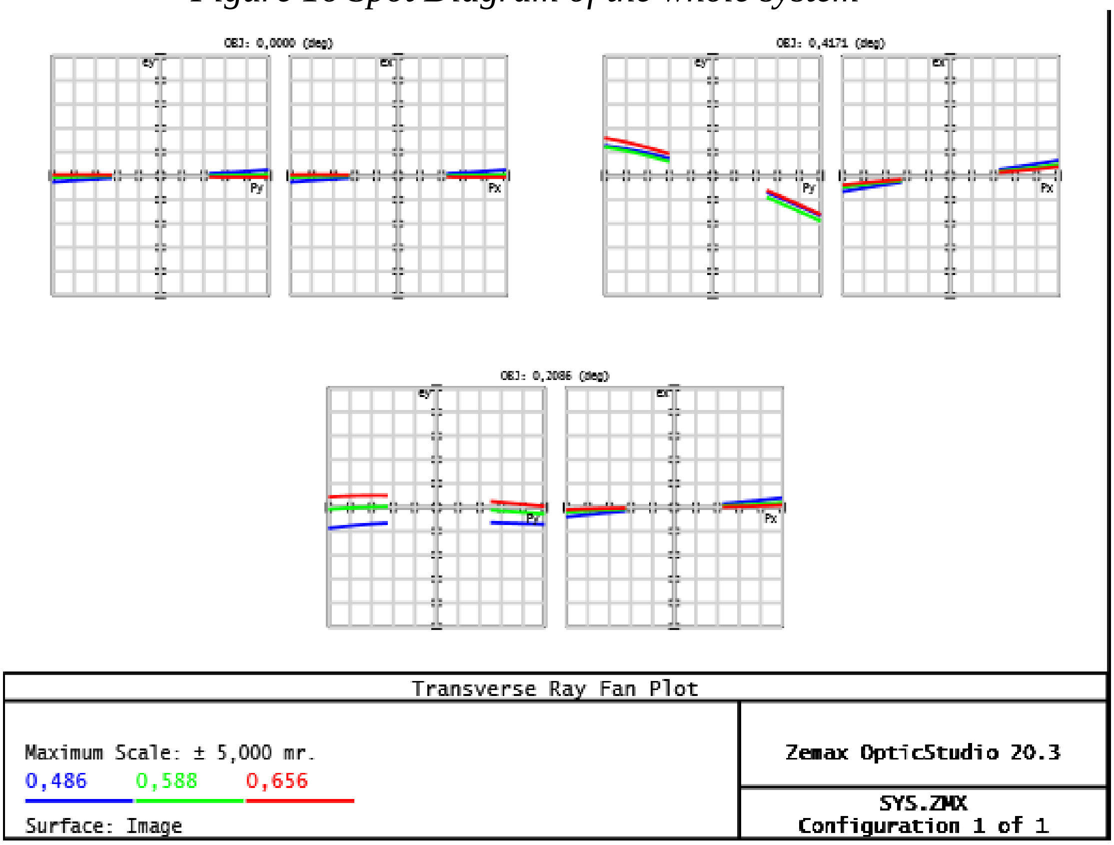


Figure 17 Ray Fan Plot of the whole system

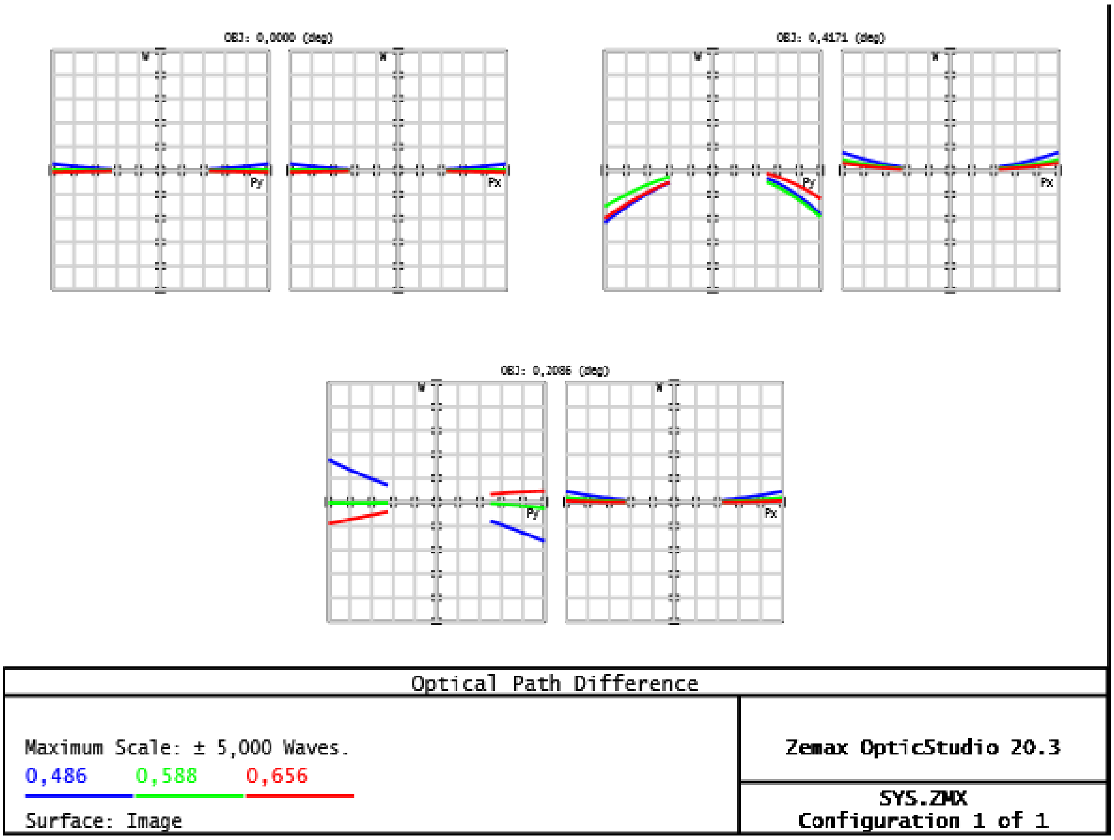


Figure 18 Optical Path Difference of the whole system

Table 17 Cardinal Points of the Whole System (the last surface is the exit pupil surface)

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm
2316261.644	-115810515.299	-46326.260	-113494253.655	2269935.385

On the whole, the image quality of this telescope is pretty good, the radii of the spots are really small, and there is hardly any spherical aberration or coma in our system. However, the severe chromatic aberration produced by the eyepiece is still there. One of the solutions is to change some of the lens materials in the eyepiece to counteract the chromatic aberration produced by each lens. Besides, there is a little astigmatism for the short-wavelength light.

3. Tolerancing Analysis

During manufacturing and assembling, it is impossible for us to totally avoid the problem of inaccuracy, and that may result in low image quality. Thus, we have to make a limitation on the inaccuracy to keep our image from being intolerable, and that is called tolerancing.

In the designed Cassegrain telescopic system, inaccuracy may occur on the width of elements, the distance between the components, the radii of spherical surfaces, the compactness of cemented surfaces, and the conic coefficient of aspherical surfaces.

Surf:Type		Radius	Thickness		Glass		Semi-Diameter	Conic
OBJ	Standard	Infinity	Infinity				Infinity	0.000
*	Standard	-1153.846	-375.000		MIRROR		62.500	-1.229
2	Standard	-750.000	437.301		MIRROR		24.660	-11.566
3	Standard	Infinity	30.402	V			9.101	0.000
4	Standard	Infinity	6.970		LZ_CTK19		11.066	0.000
5	Standard	-36.821	0.299				11.259	0.000
6	Standard	65.487	3.186		LZ_TF10		10.727	0.000
7	Standard	36.482	6.970		LZ_CTK19		10.078	0.000
8	Standard	Infinity	0.299				9.132	0.000
9	Standard	29.114	13.940		LZ_CTK19		8.640	0.000
10	Standard	-23.668	3.186		LZ_TF10		4.910	0.000
11	Standard	23.668	8.613	C			3.756	0.000
12	Standard	Infinity	-4.633E+004	M			1.969	0.000
IMA	Standard	Infinity	-				1.866E+004	0.000

5.1 Settings on Tolerance Editor

Change the criterion to RMS angular radius, use the operand TFRN to make a limitation on the surfaces that have a large radius. Use the operands TSDX, TSDY, TSTX, TSTY to make a limitation on the eccentricity and the tilt of surfaces. Then use TCON to limit conic coefficients in tolerancing for the two aspherical mirrors.

TFRN	1	-	-	0.000	-1.000	1.000
TFRN	2	-	-	0.000	-1.000	1.000
TFRN	4	-	-	0.000	-1.000	1.000
TRAD	5	-	-	-36.821	-0.200	0.200
TRAD	6	-	-	65.487	-0.200	0.200
TRAD	7	-	-	36.482	-0.200	0.200
TFRN	8	-	-	0.000	-1.000	1.000
TCON	1	-	-	-1.229	-0.200	0.200
TCON	2	-	-	-11.566	-0.200	0.200
TSDX	1	-	-	0.000	-0.050	0.050
TSDY	1	-	-	0.000	-0.050	0.050
TSTY	1	-	-	0.000	-0.050	0.050
TSTX	1	-	-	0.000	-0.050	0.050
TSDX	2	-	-	0.000	-0.050	0.050
TSDY	2	-	-	0.000	-0.050	0.050
TSTY	2	-	-	0.000	-0.050	0.050
TSTX	2	-	-	0.000	-0.050	0.050

5.2 Set Up from Tolerancing

Switch on the ray aiming option and the compensator, turn the sampling ratio to 3. This time, we will use the plot of FFT MTF, RAY FAN, and Huygens PSF to show the influence of tolerancing on our telescopic system.

The text viewer will show the changes caused by every operand. From the list of the worst offenders, we can find the operands that will cause the most significant changes.

Worst offenders:

Type			Value	Criterion	Change
TETY	1	1	-0.20000000	0.00588768	0.00498882
TETY	1	1	0.20000000	0.00588768	0.00498882
TETX	1	1	-0.20000000	0.00588765	0.00498879
TETX	1	1	0.20000000	0.00588765	0.00498879
TTHI	1	2	0.20000000	0.00190135	0.00100249
TTHI	1	2	-0.20000000	0.00183981	0.00094095
TCON	1		-0.20000000	0.00122999	0.00033113
TCON	1		0.20000000	0.00118813	0.00028927
TFRN	1		1.00000000	0.00117952	0.00028066
TFRN	1		-1.00000000	0.00113422	0.00023536

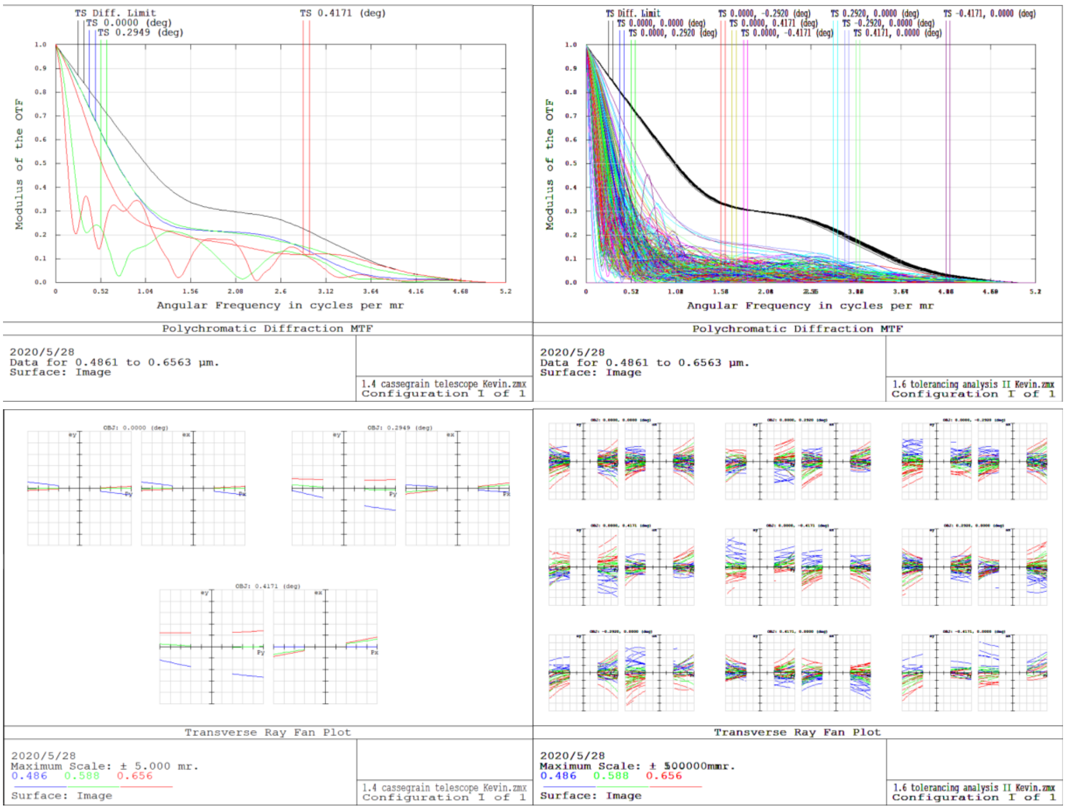
As we can see, the tilt of the two mirrors in the objective will produce the most damaging effect on the image quality of the whole system. Second come, the changes from the thickness and the position of mirrors. There is also the conic coefficient error in the primary mirror and the radius of the primary mirror. On the whole, the manufacturing and the assembly error in the objective (surface 1 and 2) will affect the system most.

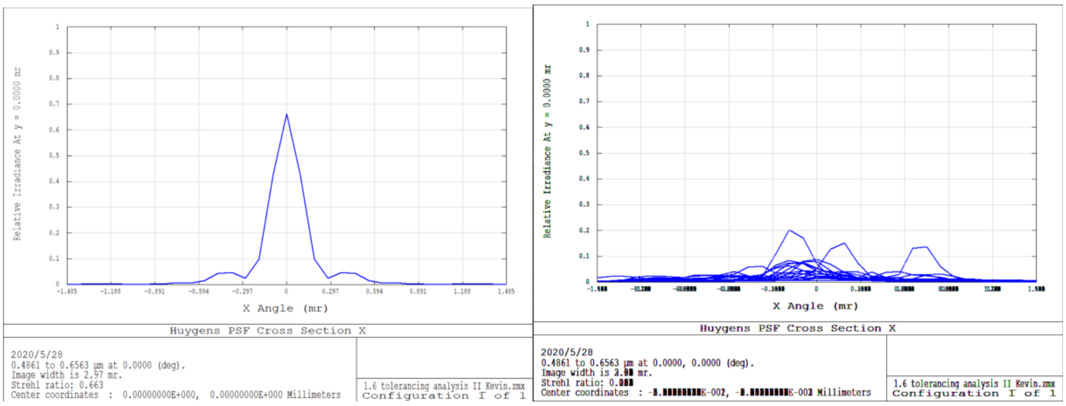
```
Monte Carlo Analysis:
Number of trials: 20

Initial Statistics: Normal Distribution

  Trial       Criterion          Change
      1      0.00255495     0.00165609
 Thickness   12:                                  -4.63262E+004
      2      0.00207477     0.00117591
 Thickness   12:                                  -4.63264E+004
      3      0.00194378     0.00104492
 Thickness   12:                                  -4.63261E+004
      4      0.00280676     0.00190790
 Thickness   12:                                  -4.63263E+004
      5      0.00335251     0.00245365
 Thickness   12:                                  -4.63262E+004
      6      0.00261509     0.00171623
 Thickness   12:                                  -4.63261E+004
      7      0.00144288     0.00054402
 Thickness   12:                                  -4.63261E+004
      8      0.00163555     0.00073669
 Thickness   12:                                  -4.63263E+004
      9      0.00218403     0.00128517
 Thickness   12:                                  -4.63264E+004
     10      0.00163442     0.00073556
 Thickness   12:                                  -4.63263E+004
     11      0.00329038     0.00239152
 Thickness   12:                                  -4.63261E+004
     12 Lens cannot be traced, tolerances may be too loose!
     13      0.00126976     0.00037090
 Thickness   12:                                  -4.63262E+004
     14      0.00395532     0.00305646
 Thickness   12:                                  -4.63262E+004
     15      0.00327196     0.00237310
 Thickness   12:                                  -4.63263E+004
     16      0.00135477     0.00045591
 Thickness   12:                                  -4.63261E+004
     17 Lens cannot be traced, tolerances may be too loose!
     18      0.00137522     0.00047636
 Thickness   12:                                  -4.63262E+004
     19      0.00119727     0.00029841
 Thickness   12:                                  -4.63261E+004
     20      0.00193052     0.00103166
 Thickness   12:                                  -4.63262E+004

Number of traceable Monte Carlo files generated: 18
```

The Figure above shows detailed information of Monte Carlo analysis.

```
Nominal      0.00089886
Best         0.00119727    Trial    19
Worst        0.00395532    Trial    14
Mean         0.00221611
Std Dev      0.00081788

Compensator Statistics:
 Thickness Surf 12:
Nominal              :    -46326.259673
Minimum              :    -46326.390368
Maximum              :    -46326.076222
Mean                 :    -46326.201611
Standard Deviation   :          0.097789


90% >        0.00332144
80% >        0.00303936
50% >        0.00200928
20% >        0.00136499
10% >        0.00123352

End of Run.
```

During the 20 (18 valid) cycles of tests, the average value of change is 0.00221611 mrad, the deviation of the compensate is 0.097789mm.





In the above three groups of Figures, those on the left show the initial situation with the image quality, and those on the right show the image quality of the systems after a Monte Carlo simulation.

Though the curves on the right are a total mess, we can still understand that the manufacturing and the assembly errors can greatly influence the image quality.

Firstly, compared with the initial MTF plot, the curves on the right have declined considerably, which means some damage to the image quality.

Secondly, from the comparison between the two ray fan plots, the tolerancing will cause severe aberrations. Though we cannot figure out the exact types of aberration from the tangled curves, by analyzing the trends and the distribution of the curves in different colors, we think that the spherical aberration, the coma and the chromatic aberration (both axial and lateral) may be the main types of aberration caused by tolerancing.

Thirdly, the Strehl ratio has drastically dropped compared to the initial situation, which means that tolerancing will make the energy distribution on the image plane more dispersed, which will certainly affect the visual quality of the image.

ITMO University

Faculty of ________________

Project report on

Telescope System Design With Lens Inverting System

Student:______________

Prof.:_______________

Changchun

20__

Initial Parameters and Calculation

Table 1 – Initial parameters

Angular magnification	Field of view in the image space	Entrance pupil diameter	F-number (objective)
6	2ω'=50°	30 mm	4

1) Calculate the first-order properties for the system and its components (find the focal lengths of the components, their diameter, F-numbers, and other characteristics).

Magnification of system:

$$\Gamma = -\frac{f'_{ob}}{f'_{ep}} \cdot \beta_{rls}$$

$$\beta_{rls} = -1$$

$$\Gamma = 6$$

Angular field of view in the object space:

$$tg\omega = tg\omega'/\Gamma;$$

$$tg\omega = \frac{tg25}{6} = 0.0777, \omega = 4.32°;$$

Focal lengths of the objective:

$$f'_{ob} = D \cdot F/\#;$$

$$f'_{ob} = 30 \cdot 4 = 120mm;$$

Focal lengths of the eye-piece:

$$f'_{ep} = f'_{ob}/\Gamma;$$

$$f'_{ep} = \frac{120}{6} = 20mm;$$

Exit pupil diameter:

$$D' = D/\Gamma$$

$$D' = \frac{30}{6} = 5mm$$

F-number of the eye-piece:

$$F/\#_{ep} = f'_{ep}/D';$$

$$F/\#_{ep} = \frac{20}{5} = 4.$$

The telescope objective is a cemented doublet lens with the characteristics as follows:

- Focal length f'_{ob}=120mm;

- Entrance pupil diameter D_{ob}=D=30mm;

- Angular field of view $2\omega_{ob}=2\omega$=8.64°.

The telescope **reversed** eye-piece is to have the following characteristics:

- Focal length f'_{ep}=20mm;
- F-number of the eyepiece $F/\#_{ep}$=4;
- Angular field of view $2\omega_{ep}=2\omega'$=50°;

Table 2 – Ideal model of the designed telescope

	Surface Type		Comm	Radius	Thickness		Material	Focal Length	Coatin	Semi-Diamete
0	OBJECT	Standard		Infinity	Infinity					Infinity
1	STOP	Paraxial			140,000			120,000		15,000
2		Paraxial			23,333	C		20,000		13,076
3	IMAGE	Standard		Infinity	-					2,500

Layout of the system:

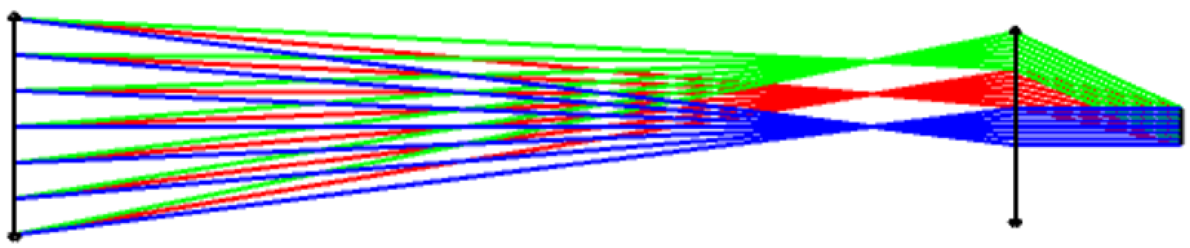


Figure 1 – Ideal model of the designed telescope

2) Choose the eye-piece from the catalog.

- f'_{cat} is to be twice as large or half as large as f'_{ep};
- $F/\#_{cat}$ is to be smaller than $F/\#_{ep}$;
- $2\omega_{cat}$ is to be higher than $2\omega_{ep}$.

The characteristics of the catalog eye-piece:

- Focal length f'_{cat}=15.6mm;
- F-number of the eye-piece $F/\#_{cat}$=3.9;
- Angular field of view $2\omega_{cat}$=56°;

3) Set the eye-piece in Zemax Optic Studio software. Analyze the first-order properties, the layout, the spot diagrams and the aberration plots.

Table 3 – Lens Data of the reversed eye-piece from the catalog

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
				1.000000
1 STOP	infinity	12.93		1.000000
2	-340.40	2.00	TF4	1.746231
3	52.970	8.00	CTK3	1.662240
4	-17.989	0.10		1.000000
5	66.070	4.00	CTK3	1.662240
6	-66.070	0.10		1.000000
7	28.910	10.00	CTK3	1.662240
8	-12.794	2.00	TF4	1.746231
	41.880	5.89		1.000000

Table 4 – Cardinal points of the eye-piece from the catalog

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm
15.61	-11.45	5.94	4.16	-9.67

Use the tool “*Make focal*” for the eye-piece, correct the aperture and the field of view. The resulting lens data for the eye-piece are given in Table 5.

Table 5 – Lens Data of the reversed eye-piece

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
1 STOP	Infinity	16,541		1.000000
2	-436.156	2.563	TF4	1.746231
3	67.871	10.234	CTK3	1.662240
4	-23.049	0.128		1.000000
5	84.656	5.125	CTK3	1.662240
6	-84.656	0.128		1.000000
7	36.984	12.813	CTK3	1.662240
8	-16.393	2.563	TF4	1.746231
	53.661			1.000000

Table 6 – Cardinal points of the eye-piece

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm
20.00	-14.68	7.61	5.32	-12.39

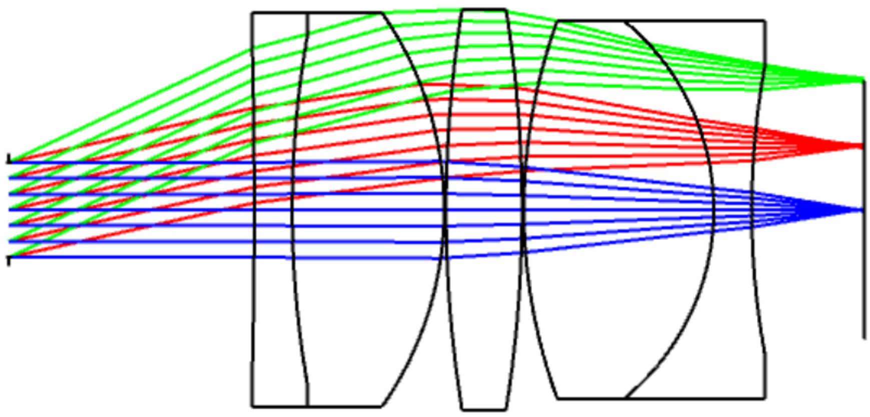


Figure 2 – Layout of the reversed eye-piece

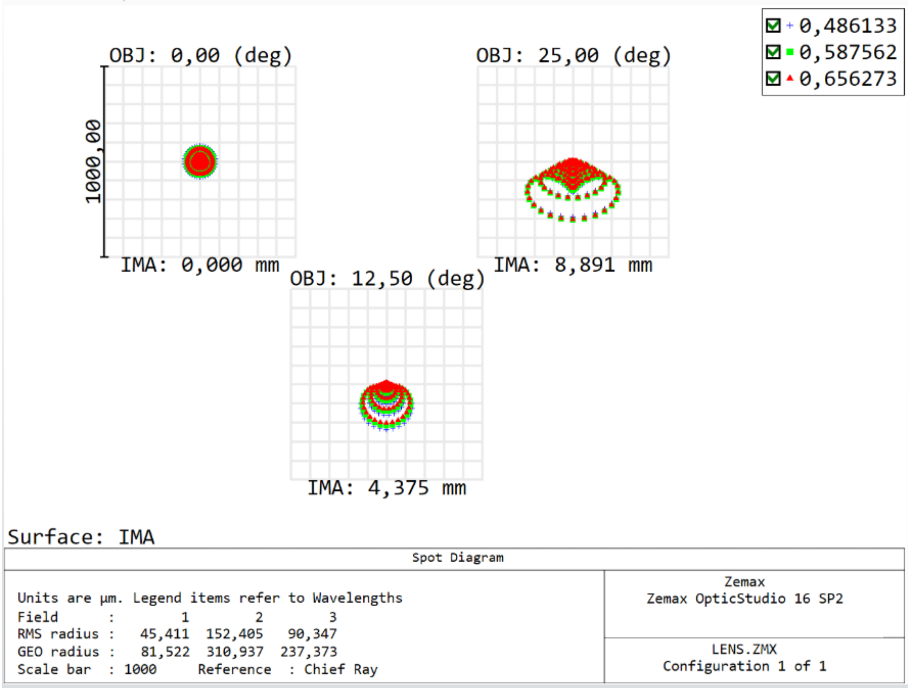


Figure 3 – Spot Diagram of the reversed eye-piece

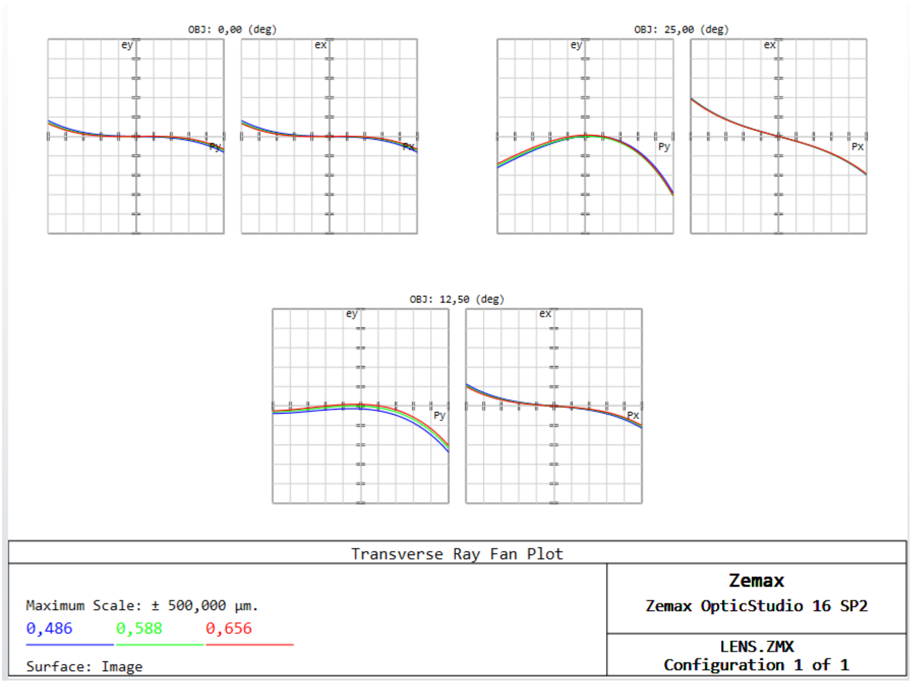


Figure 4 – Ray Fan Plot of the reversed eye-piece

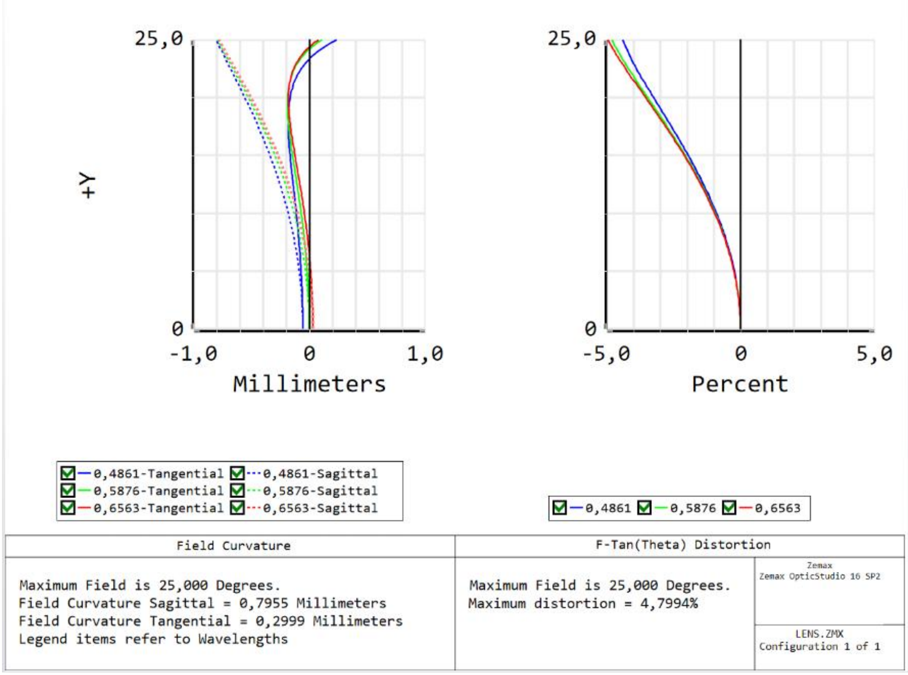


Figure 5 – Field curvature/distortion of the reversed eye-piece

Analyze the image quality of the eye-piece:

According to the spot diagram of the observation eyepiece, it can be seen that although the radius of the Airy disk is not very large, there is still a certain coma affecting the image quality. According to the optical path difference, it can be seen that there is still a small deviation from the ray , which shows that the image is still not perfect, and because of the presence of aberration it will still affect the image quality.

4) Calculate the first-order properties and perform the aberration correction of the objective. Evaluate the image quality of the objective.

The telescope objective is a cemented doublet lens

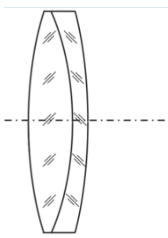


Figure 6 – Cemented doublet lens

Choose the pair of glass: N-SF5–N-K5

Calculation in relative units:

$$\{\varphi_1+\varphi_2=1;\ \frac{\varphi_1}{\nu_1}+\frac{\varphi_2}{\nu_2}=0$$

$$\varphi_1 = \frac{\nu_1}{\nu_1 - \nu_2}; \quad \varphi_1 = \frac{32.209847}{32.209847 - 59.482671} = -1.181024$$
$$\varphi_2 = -\frac{\nu_2}{\nu_1 - \nu_2}; \varphi_2 = -\frac{59.482671}{32.209847 - 59.482671} = 2.181024$$

$$\nu = \frac{n_e - 1}{n_{F'} - n_{C'}};$$

$$\varphi_1 = (n_{e1} - 1) \cdot \left(\frac{1}{r_1} - \frac{1}{r_2}\right); \qquad \varphi_1 = (1.672697 - 1) \cdot \left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$
$$\varphi_2 = (n_{e2} - 1) \cdot \left(\frac{1}{r_2} - \frac{1}{r_3}\right); \qquad \varphi_2 = (1.522489 - 1) \cdot \left(\frac{1}{r_2} - \frac{1}{r_3}\right);$$

If r_3 is infinity, then:

$$r_1 = 0.413454, r_2 = 0.239561, r_3 = infinity$$

Calculate the radii in mm:

$$R_1 = r_1 \cdot f'_{ob}; \; R_1 = 0.413454 \cdot 120 = 49.61mm$$
$$R_2 = r_2 \cdot f'_{ob}; \; R_2 = 0.239561 \cdot 120 = 28.75mm$$
$$R_3 = r_3 \cdot f'_{ob}; \; R_3 = infinity$$

Choose the thickness of the lenses – 3 mm for the first (negative) lens, 10 mm for the second (positive) lens.

5) Set the objective in Zemax Optic Studio software. Analyze the first-order properties, the layout, the spot diagrams and the aberration plots.

Optimize the objective using the radii as variables. Correct the spherical aberration, the coma, the chromatic aberration, and control the focal length.

Table 7 – Lens Data of the objective

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
1	49.373	3	SF5	1.6727
2	27.691	10	K5	1.5225
3	infinity			1

Table 8 – Cardinal points of the objective

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm
-120	-121.17	110.51	-1.17	-9.50

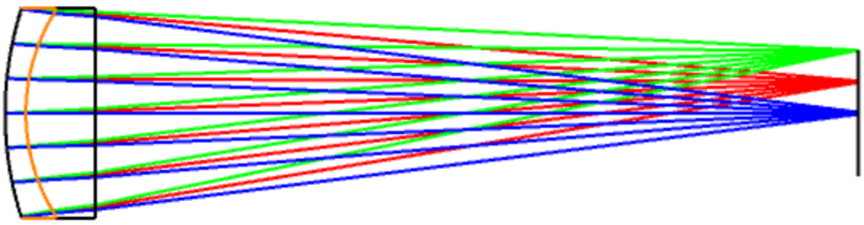


Figure 7 – Layout of the objective

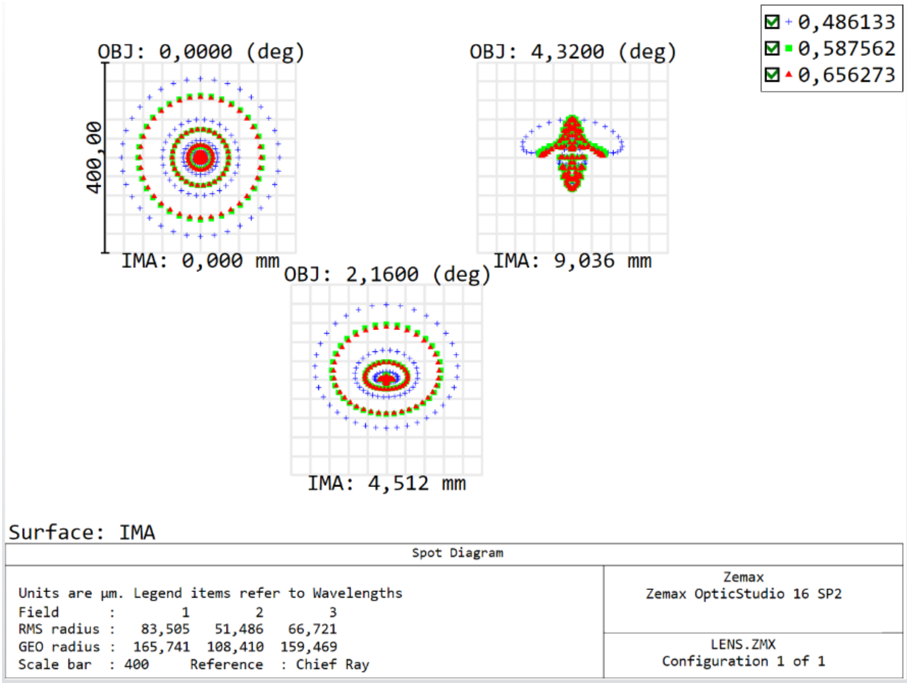


Figure 8 – Spot Diagram of the objective

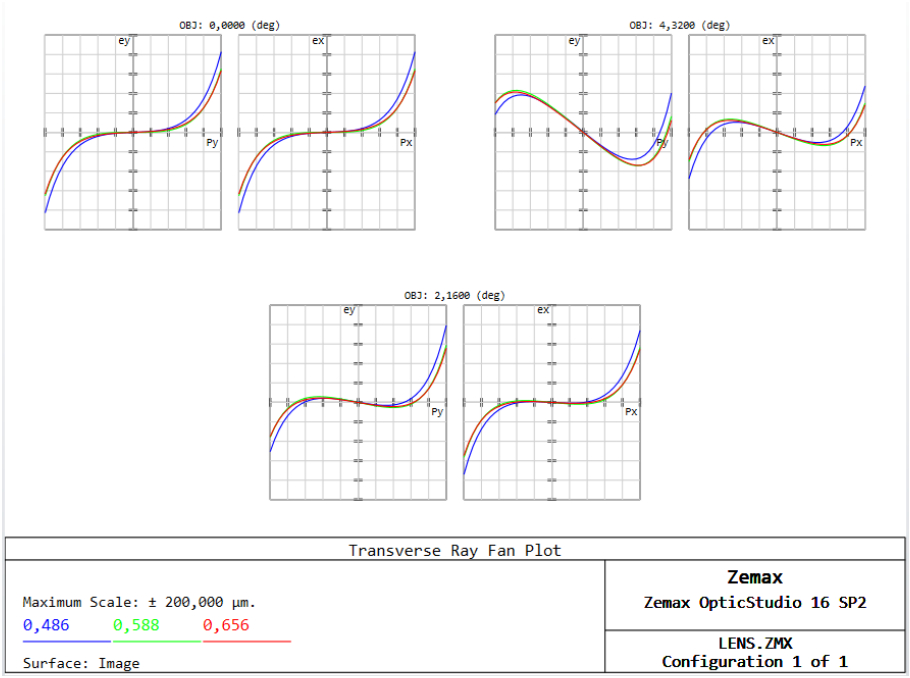


Figure 9 – Ray Fan Plot of the objective

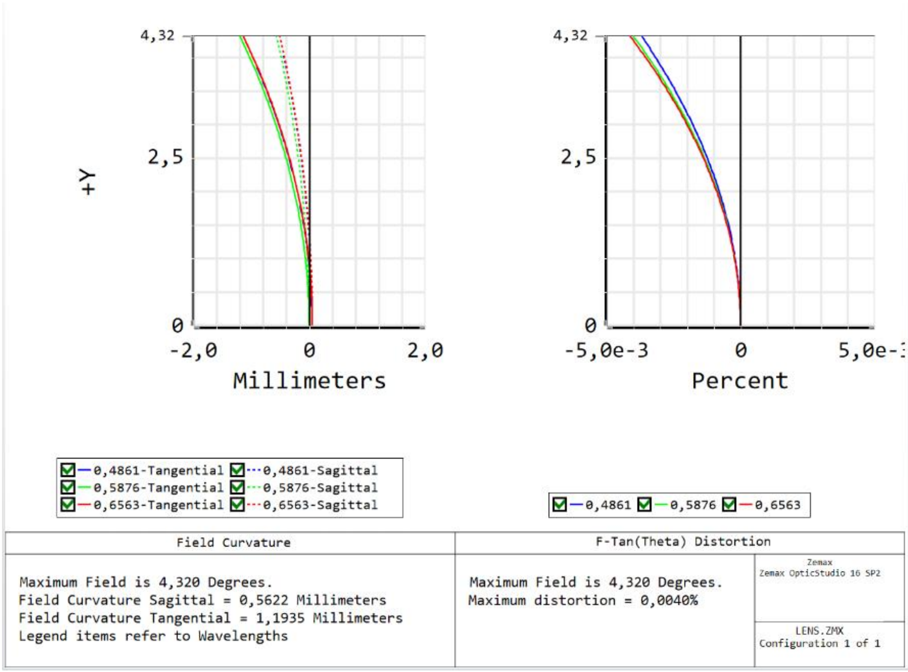


Figure 10 – Field curvature/distortion of the objective

Analyze the image quality of the objective:

Although optimized, it can be seen that the image quality is affected by a certain degree of spherical aberration. By observing the ray fan aberration image, it can be seen that there is still a certain aberration in the vertical axis direction. At the same time, it can be seen that the image quality is also affected by a little optical path difference.

6) Compose the system of the objective and the eye-piece, evaluate the image quality

Switch on “afocal image space”.

Table 9 – Lens Data of the system

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
1	49.216	3	SF5	1.6727
2	27.603	10	K5	1.5225
3	infinity	110,506		1.0000
4	infinity	7,621		1.0000
5	-53.661	2.6	LZ_TF4	1.7400
6	16.393	12.8	LZ_CTK3	1.6595
7	-37.042	0.13		1.0000
8	84.656	5.1	LZ_CTK3	1.6595
9	-84.656	0.13		1.0000
10	23.049	10.3	LZ_CTK3	1.6595
11	-67.871	2.6	LZ_TF4	1.7400
12	436.156	18.5		1.0000
13	infinity			1.0000

Table 10 – Cardinal points of the system

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm
infinity	infinity	infinity	infinity	infinity

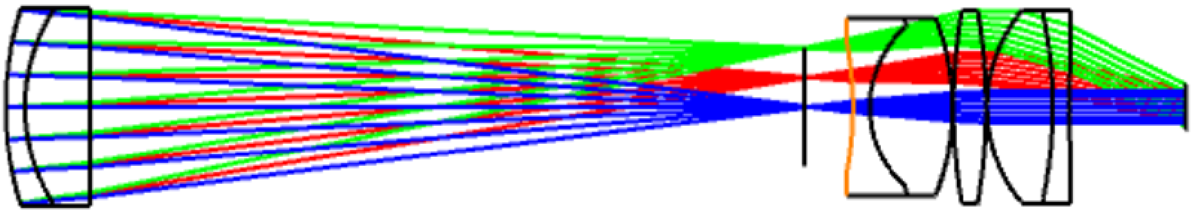


Figure 11 – Layout of the system

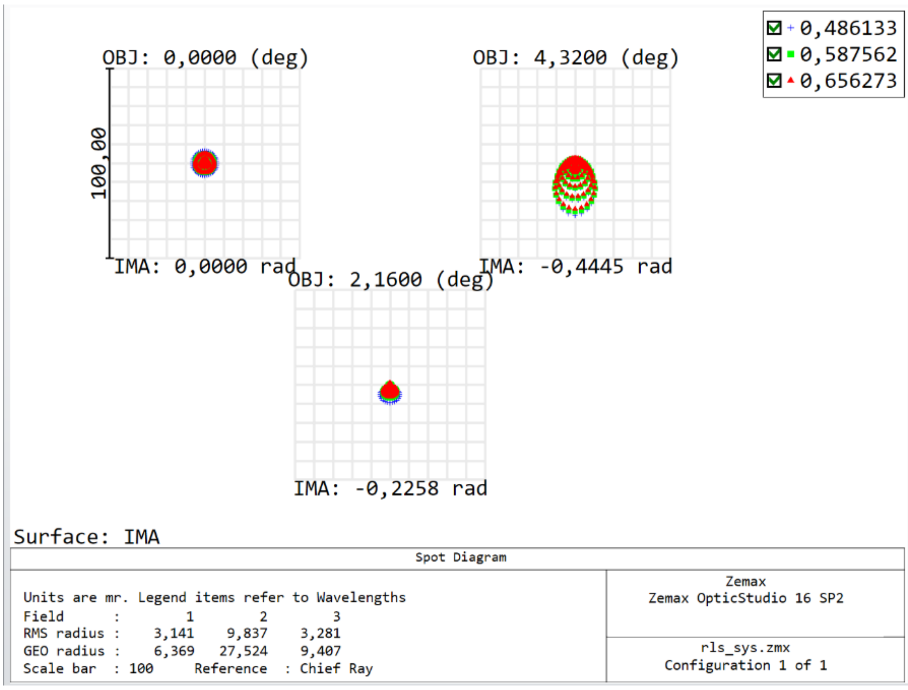


Figure 12 – Spot Diagram of the system

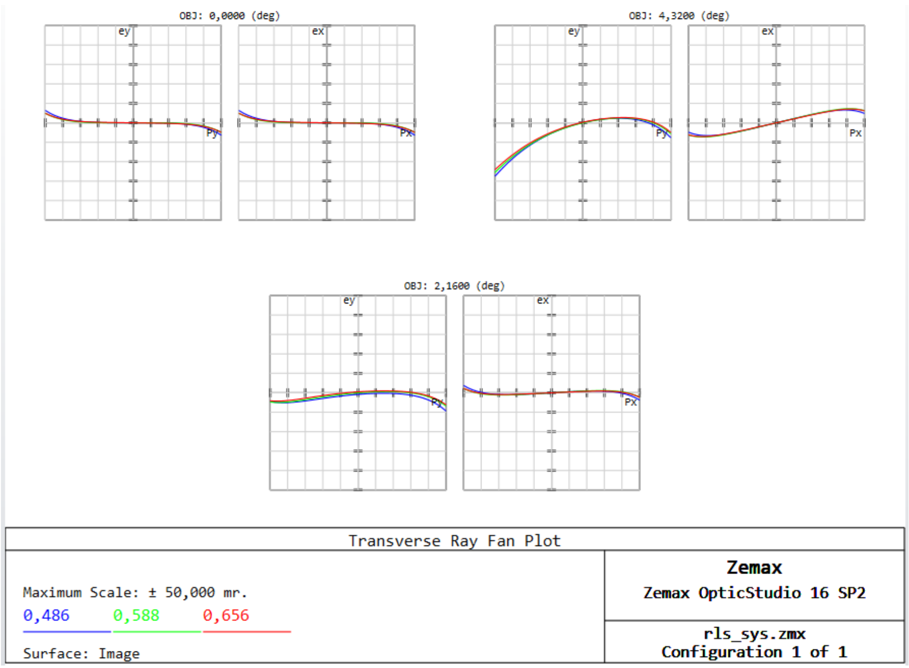


Figure 13 – Ray Fan Plot of the system

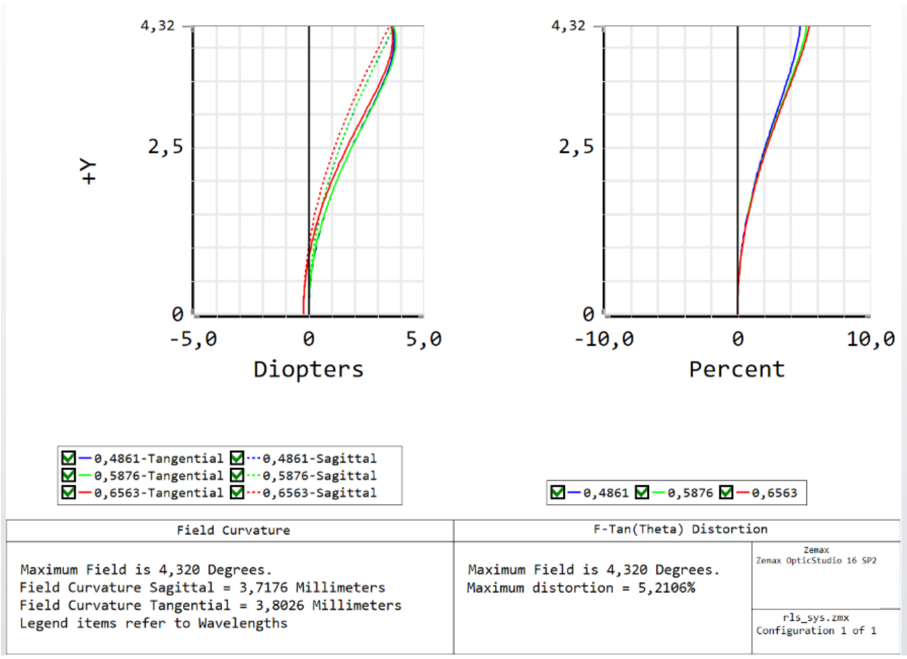
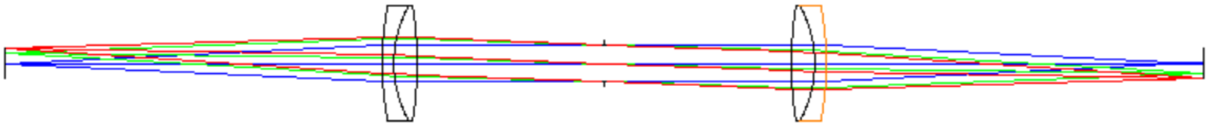


Figure 14 – Field curvature/distortion of the system

Analyze the image quality system:

According to the spot diagram, it can be seen that the image quality of the synthesized system is still very little affected by the spherical aberration and the coma, and this can be seen from the radius of the diffuse spot and Airy disk. And it can be seen that the image is still not very good. The image quality for the non-axial points is affected by Field curvature**.** Overall, although the performance of images is not perfect, it is within the expected range.

7) Add a lens inverting system



Calculate the second doublet of the inverting lens system.
The largest lens diameter:

$$D_0 = 2tg\omega \cdot f'_{ob} = 2 \times tg4.32° \times 120 = 18.13mm$$

The focal length of the second doublet of the lens inverting system:

$$f'_{rls} = \frac{D_0 \cdot f'_{ob}}{D} = \frac{18.1299 \cdot 120}{30} = 72.52mm$$

F-number of the second doublet of the reversing lens system:

$$\frac{f'_{rls}}{D_0} = \frac{72.5196}{18.1299} = 4$$

Angular field of view of the second doublet of the lens inverting system:

$$2\omega = 2arctg\left(\frac{D_0}{2f'_{rls}}\right) = 2arctg\left(\frac{18.1299}{2 \times 72.5196}\right) = 2 \times 7.1247°$$

Object height for the lens inverting system:

$$y = f'_{rls}tg\omega = 120 \times tg7.1247° = 15mm$$

Calculate the doublet lens following step 4 for the objective calculation.
Choose pair of glass: N-K5 – N-SF5

Calculation in relative units:

$$\{\varphi_1 + \varphi_2 = 1 \; \frac{\varphi_1}{\nu_1} + \frac{\varphi_2}{\nu_2} = 0$$

$$\varphi_1 = \frac{\nu_1}{\nu_1 - \nu_2}; \qquad \varphi_1 = \frac{59.482671}{59.482671 - 32.209847} = 2.1810235$$

$$\varphi_2 = -\frac{\nu_2}{\nu_1 - \nu_2}; \qquad \varphi_2 = -\frac{32.209847}{59.482671 - 32.209847} = -1.1810235$$

$$\nu = \frac{n_e - 1}{n_{F'} - n_{C'}};$$

$$\varphi_1 = (n_{e1} - 1) \cdot \left(\frac{1}{r_1} - \frac{1}{r_2}\right); \quad \varphi_1 = (1.522489 - 1) \cdot \left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

$$\varphi_2 = (n_{e2} - 1) \cdot \left(\frac{1}{r_2} - \frac{1}{r_3}\right); \quad \varphi_2 = (1.672697 - 1) \cdot \left(\frac{1}{r_2} - \frac{1}{r_3}\right);$$

If $r_1 = infinity, then\ r_2 = -0.23956, r_3 = -0.413451$

Radii in mm:

$R_1 = r_1 \cdot f'_{rls};\ R_1 = infinity$

$R_2 = r_2 \cdot f'_{rls};\ R_2 = -0.23956 \times 72.5196 = -17.37mm$

$R_3 = r_3 \cdot f'_{rls};\ R_3 = -0.413451 \times 72.5196 = -29.98mm$

Determine the thicknesses and optimize the system. The changing parameters are the radii, and they affect the effective focal length and the aberrations to consider.

The first doublet of the reversing lens system is the reversed second doublet of the reversing lens system.

Table 11 – Lens Data of the second doublet of the reversing lens system

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
1	201.232	10	K5	1.5225
2	-17.370	5	SF5	1.6727
3	-34.180			1.0000

Table 12 – Cardinal points of the second doublet of the reversing lens system

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm
72.52	-62.756	72.563	9.764	0.043

Table 13 – Cardinal points of the first doublet of the reversing lens system

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm
72.52	-72.563	62.756	-0.043	-9.764

Distance between the doublet lenses:

$$d_{1-2} = f'_{rls} = 72.52mm$$

Distance between the objective and the first component of the lens inverting system:

$$d_{ob-1} = S'_{ob} - S_{F1} = 110.469 - \square - 65.978\square = 176.45mm$$

Distance between the second doublet of the lens inverting system and the eye-piece:

$$d_{2-ep} = S'_{F2} - S_{Fep} = 65.978 - 1.848556 = 64.13mm$$

Aperture Stop position between the first and the second doublets of the lens inverting system:

$$d_{AS} = \frac{d_{1-2}}{2} = \frac{72.5196}{2} = 36.26mm$$

Paraxial magnification -1

Table 14 – System Data of the reversing lens system

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
obj		72.563		1
1	34.18	5	SF5	1.6727
2	17.37	10	K5	1.5225
3	-201.23	36.26		1
Stop	Infinity	36.26		1
5	201.23	10	K5	1.5225
6	17.37	5	SF5	1.6727
7	34.18	72.563		

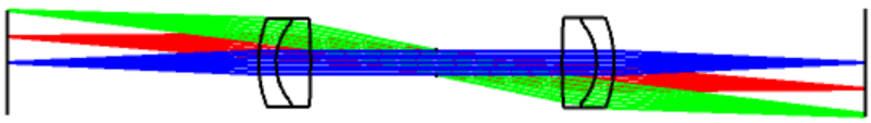


Figure 15 – Lay Out of the lens inverting system

8) Collective lens calculation

Entrance pupil position of the collective lens:

$-a_{Pcol} = f'_{ob} = 120mm;$

Exit pupil position of the collective lens:
$a'_{Pcol} = f'_{lis} + a_{Plis1} = 72.5196 + 72.5196 = 145.04mm$;

Exit pupil position of the first lens of the reversing system:

$a'_{Plis1} = d_{AS} = 36.26mm$;

Entrance pupil position of the first lens of the reversing system

$$a_{Plis1} = \frac{f'_{lis1} \cdot a'_{Plis1}}{f_{lis1} - a'_{Plis1}} = \frac{72.5196 \cdot 36.2598}{72.5196 - 36.2598} = 72.52mm$$

$$f'_{col} = \frac{a'_{Pcol} \cdot a_{Pcol}}{a_{Pcol} - a'_{Pcol}} = \frac{145.0392 \cdot (-120)}{(-120) - 145.0392} = 65.67mm$$

Table 15 – System Data of the collective lens

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
1	Infinity	5	LZ_K8	1.5164
2	-33.8849			1

9) Add the lens inverting system into the telescope

Table 16 – Lens Data of the telescope system

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
1	49.216	3	SF5	1.6727
2	27.603	10	K5	1.5225
3	infinity	107,21		1
4	Inf	5.	LZ_K8	1.5164
5	-33.885	72.563		1
6	34.18	5	SF5	1.6727
7	17.37	10	K5	1.5225
8	-201.23	36.26		1
Stop	Infinity	36.26		1
10	201.23	10	K5	1.5225
11	17.37	5	SF5	1.6727
12	34.18	72.563		1
13	infinity	7,621		1
14	-53.661	2.6	LZ_TF4	1.7400
15	16.393	12.8	LZ_CTK3	1.6595
16	-37.042	0.13		1
17	84.656	5.1	LZ_CTK3	1.6595
18	-84.656	0.13		1
19	23.049	10.3	LZ_CTK3	1.6596
20	-67.871	2.6	LZ_TF4	1.7400
21	436.156	16.8		1
22	infinity			1

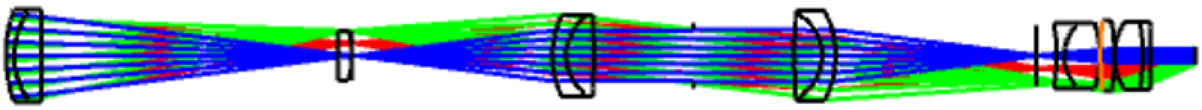


Figure 16 – Layout of the whole system

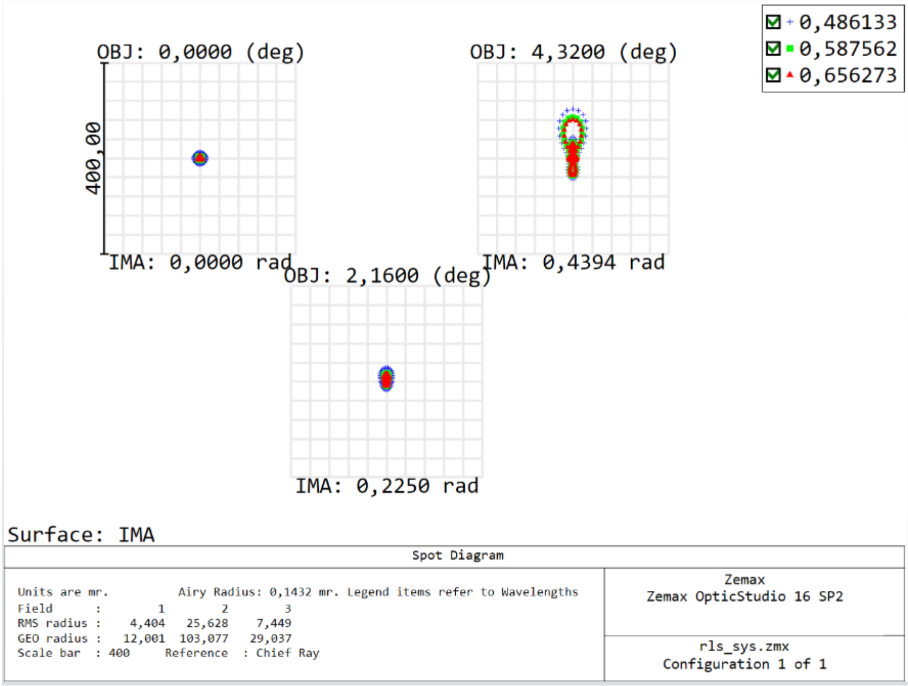


Figure 17 – Spot Diagram of the whole system

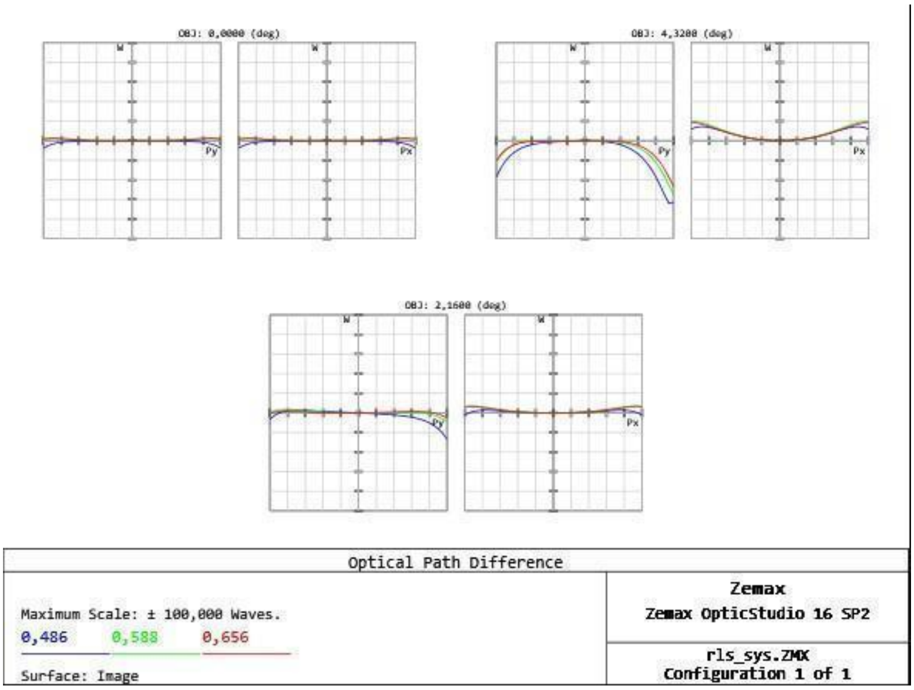


Figure 18 – Optical Path Difference of the whole system

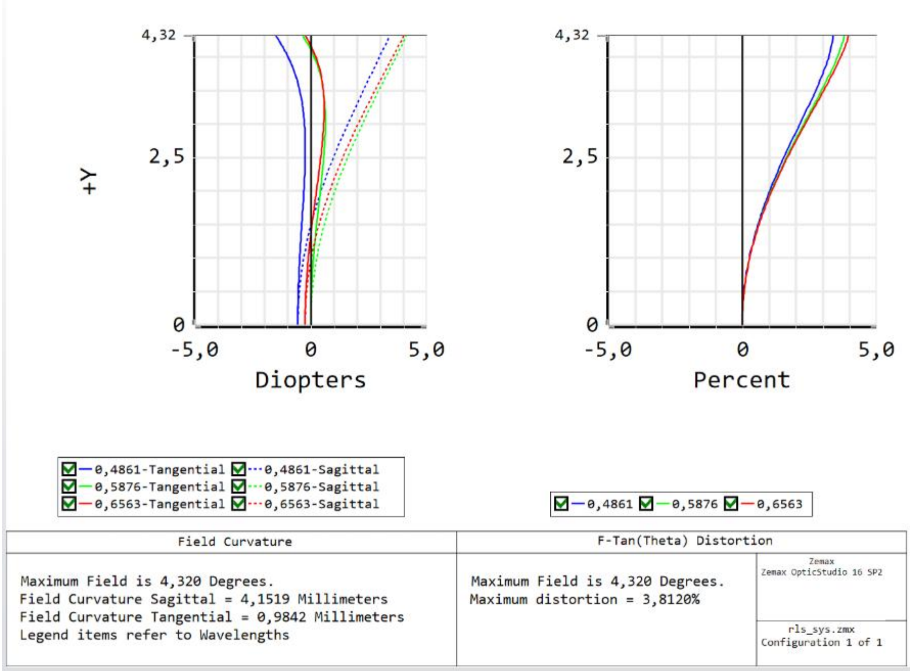


Figure 19 – Field curvature/distortion of the whole system

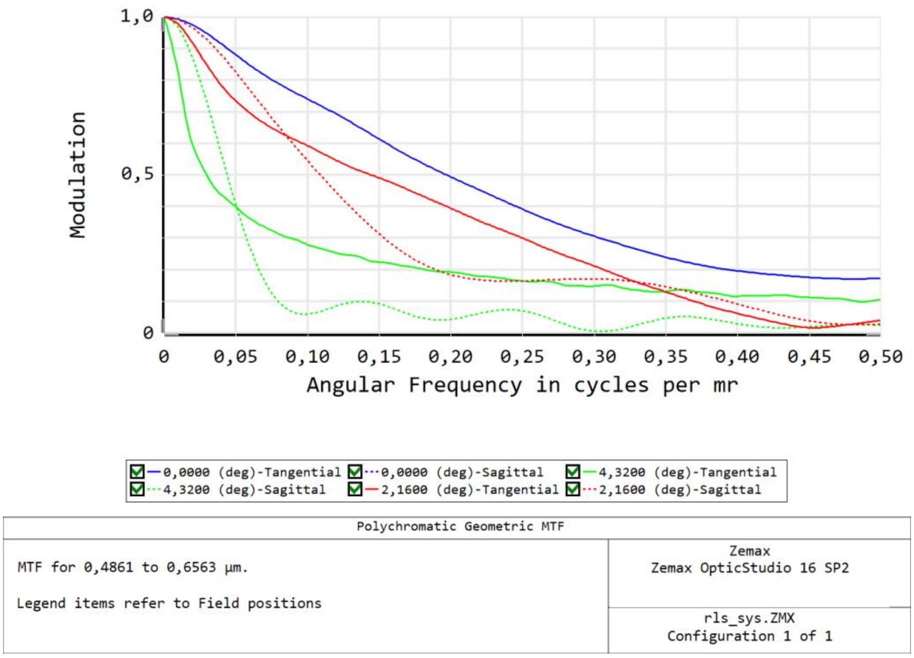


Figure 20 – MTF of the whole system

Analyze the image quality:

From the perspective of the entire system, as observed from the Figures for the aberrations, the spot diagrams, and the optical path differences, the image quality is affected to a certain extent by the spherical aberration, the coma, and the astigmatic shifts. However, in addition, the optical path difference is large, each factor that affects the image quality of the system is not very important, and the radius of the diffuse spot and Airy disk are not very large, indicating that the aberration still has a certain effect on the image, but not very large. Although the image quality produced by the system is not perfect, it is still acceptable.

10) Conclusion and comments about the resulting system

Through the calculation of the paraxial optical path we selected the eyepiece, calculated the design and optimized the objective lens. Synthesizing the preliminary system, and then adding the calculated reversing lens system, adjusting the optical path by placing a calculated collective lens, and finally forming the designed telescope system were performed.

Although the objective lens and the reversing lens system have been optimized during the design process, there is still a certain aberration effect in the final telescope system. However, the smooth synthesis and the image quality of the entire system are still as expected. Although the imaging cannot be perfect, the designed system and the effects of aberrations are still acceptable.

Example of designing a telescope system with a prism system

ITMO University

Faculty of ______________

Project report on

Telescope System Design with Prism System

Student:____________

Prof.:_____________

Changchun

20__

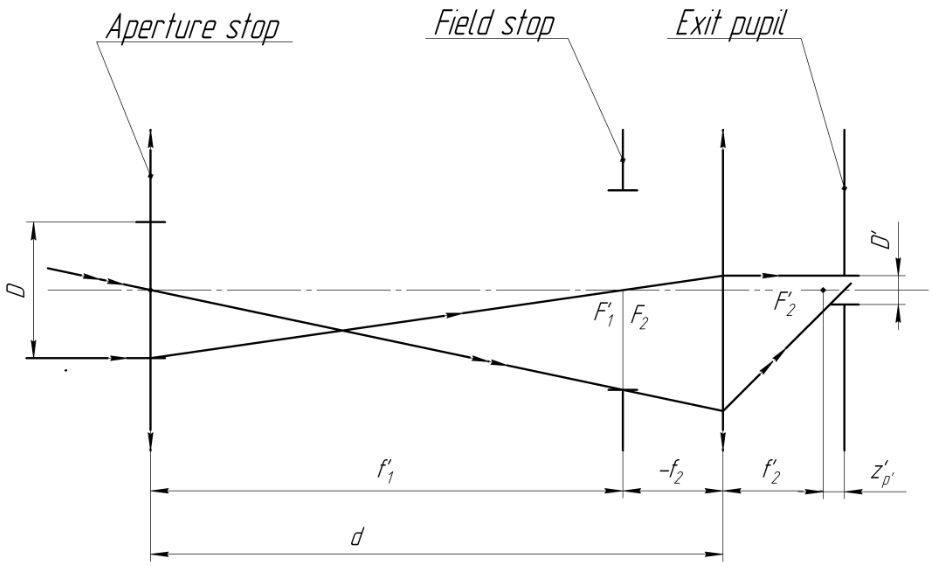


Figure 1 – Basic scheme. Kepler system.

Initial Parameters and Calculation

Table 1 – Initial parameters

Angular magnification	Angular field view in the image space	Entrance pupil diameter mm	F number of the objective
25	$2\omega' = 35°$	80	F/9

1) Calculate the first-order properties for the system and its components (find the focal lengths of the components, their diameter, F-numbers, and other characteristics).

Magnification of the system:

$$\Gamma = -\frac{f'_{ob}}{f'_{eye}} \cdot \beta_{prizm}$$

$$\beta_{prizm} = -1$$

Angular field of view in the object space:

$$tg\omega = tg\omega_{ob} = tg\omega'/\Gamma;$$

$$tg\omega = \frac{tg\omega'}{\Gamma} = \frac{tg17{,}5}{25} = 0{,}013$$

$$\omega = 0{,}75°$$

Focal lengths of the objective:

$f'_{ob} = D \cdot F/\# = 80 \times 9 = 720\ mm$

Focal lengths of the eye-peace:

$f'_{ep} = f'_{ob}/\Gamma$ =720/25=28,8 mm

Exit pupil diameter:

$D' = D/\Gamma$ = 80/25 = 3,2 mm

F-number of the eye-piece:

$F/\#_{ep} = f'_{ep}/D'$;

$F/\#_{ep} = 28{,}8/3{,}2 = 9\ mm$

The telescope objective is a cemented doublet lens with the following characteristics:

- Focal length f'_{ob}=720 *mm*;
- Entrance pupil diameter D_{ob}=D=80 *mm*;
- Angular field of view $2\omega_{ob}$=2ω=1,5°;

Table 2 –Lens data

# Surf: type	Radii	Thickness	Focal length	Semi- Diameter
OBJ	infinity	Infinity		infinity
STO	Paraxial	748,8	720	40,00
2	Paraxial	29,952	28,8	11,01
IMA	infinity	-		1,60

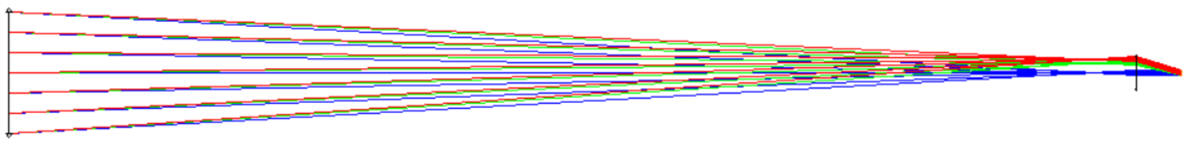


Figure 2 – Ideal model of the designed telescope

The telescope **reversed** eye-piece is to have the following characteristics:

- Focal length f'_{ep}=28,8 *mm*;
- F-number of the eyepiece $F/\#_{ep}$=9;
- Angular field of view $2\omega_{ep}$=2ω'=35°;

11) Choose the eye-piece from the catalog.

f'_{cat} is to be twice as large or half as large as f'_{ep};

$F/\#_{cat}$ is to be less than $F/\#_{ep}$;

$2\omega_{cat}$ is to be more than $2\omega_{ep}$.

The characteristics of the catalog eye-piece:

- Focal length f'_{cat}=24 *mm*;
- F-number of the eye-piece F/$\#_{cat}$=4;
- Angular field of view $2\omega_{cat}=71°$;

12) Set the eye-piece in Zemax Optic Studio software. Analyze the first-order properties, the layout, the spot diagrams and the aberration plots.

Table 3 – Lens Data of the eye-piece from the catalog

# sur	Radii	thickness	Semi-Diameter	Glass	n
STOP		14,00	3		1,00000
1	-222,80	6	12,27	LZ_K8	1,51638
2	-22,70	0,3	13,03		1,00000
3	139,32	3	14,70	LZ_TF4	1,740025
4	27,80	11	15,55	BK8	1,5202152
5	-40,00	0,3	16,07		1,00000
6	31,62	8	17,71	BK8	1,5202152
7	115,88	14,93	17,27		1,00000
Im			15,65		1,00000

Table 4 – Cardinal points of the eye-piece from the catalog

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm
25,127485	-14,912470	1,909769	10,215014	-23,217716

Apply the "Make focal" tool to the eye-piece, correct the aperture and the field of view.

Table 5 – Lens Data of the eye-piece

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
STOP	infinity	16,023		1,00000
2	-254,995	6,867	BK8	1,5202152
3	-25,980	0,343		1,00000
4	159,452	3,434	BK8	1,5202152
5	31,817	12,590	LZ_TF4	1,740025
6	-46,410	0,343		1,00000
7	36,189	9,156	LZ_K8	1,51638
8	132,6256	17,087		1,00000

Table 6 – Cardinal points of the eye-piece

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm
28,8	-17,140	6,365	11,687	-22,462

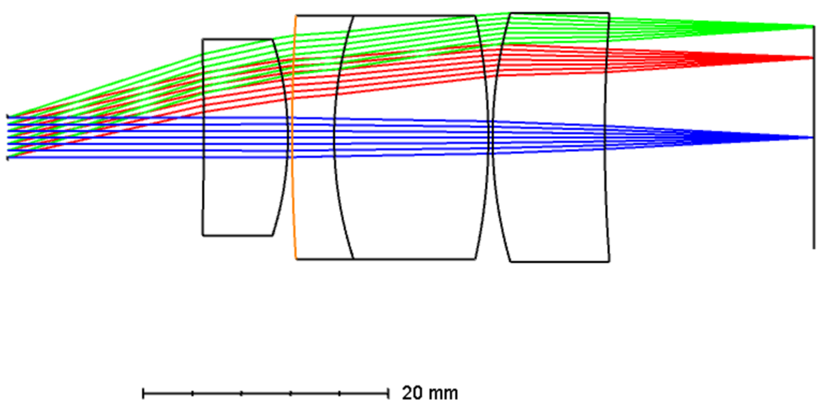


Figure 3 – Layout of the eye-piece

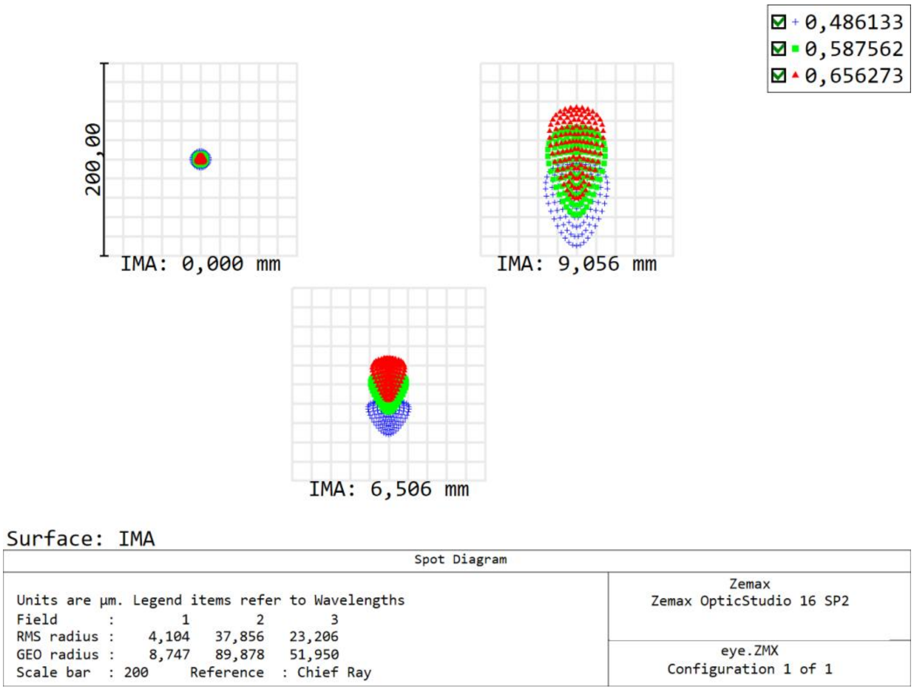


Figure 4 – Spot Diagram of the eye-piece

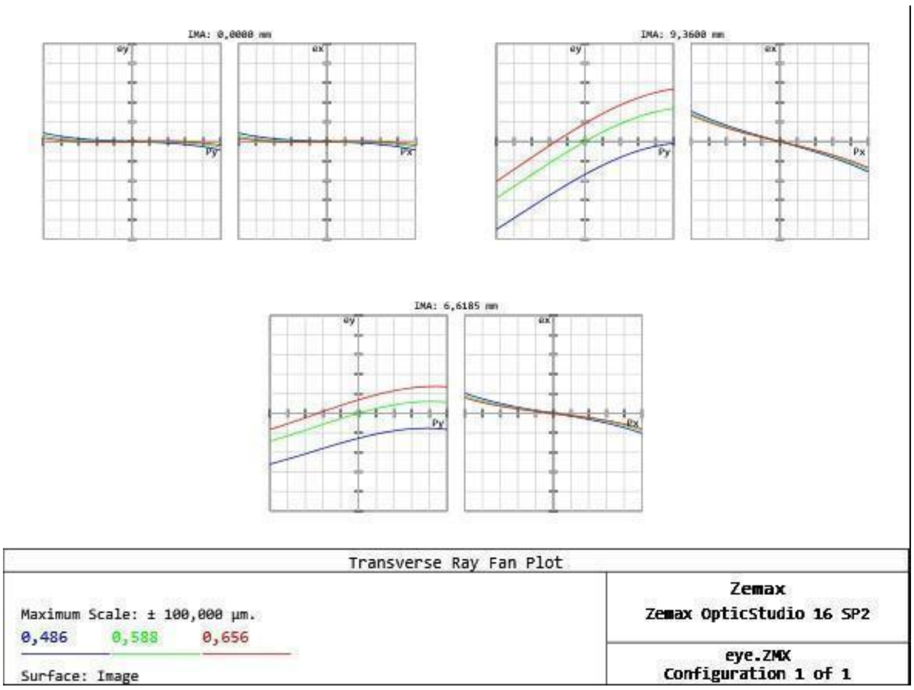


Figure 5 – Ray Fan Plot of the eye-piece

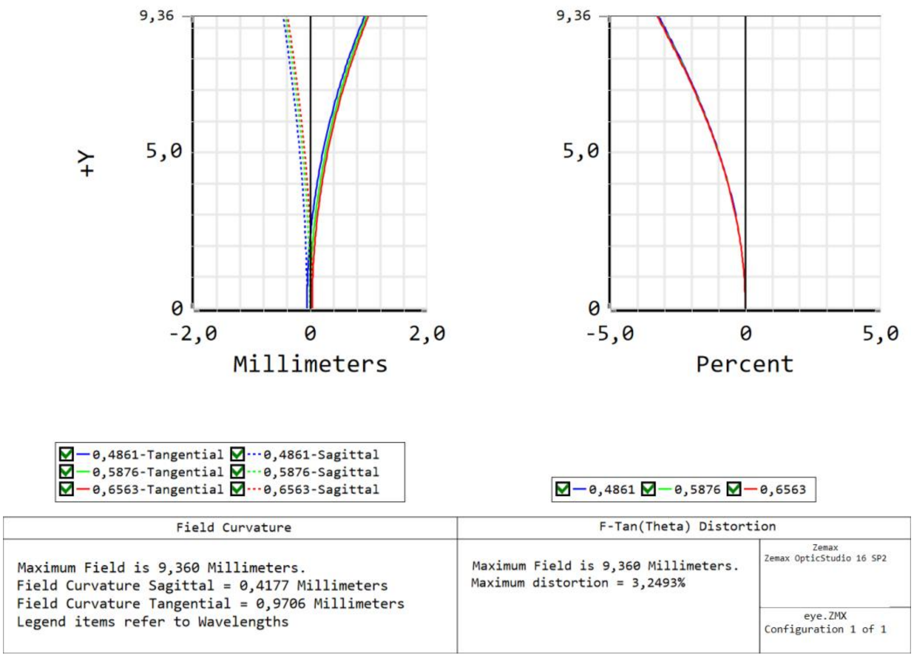


Figure 6 – Field curvature/distortion of the eye-piece

Analyze the image quality of the eye-piece:

In the region close to the axial, the image quality of the eyepiece is very good, the size of the spot is smaller than that of the Airy spot, and there are color differences in 0,707 and 1 fields.

13) Calculate the first-order properties and perform an aberration correction of the objective. Evaluate the image quality of the objective.

The telescope objective is a cemented doublet lens.

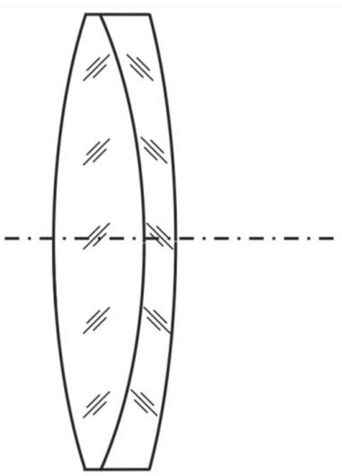


Figure 7 – Cemented doublet lens

Choose the pair of glass:

N-SF5–N-FK5

Calculation in relative units:

$$\varphi_1 + \varphi_2 = 1;\ \frac{\varphi_1}{\nu_1} + \frac{\varphi_2}{\nu_2} = 0$$

$$\nu = \frac{n_e - 1}{n_{F'} - n_{C'}};$$

$$\varphi_1 = (n_{e1} - 1) \cdot \left(\frac{1}{r_1} - \frac{1}{r_2}\right);$$

$$\varphi_2 = (n_{e2} - 1) \cdot \left(\frac{1}{r_2} - \frac{1}{r_3}\right);$$

$$\varphi_1 = \frac{\nu_1}{\nu_1 - \nu_2} = -0{,}8453$$

$$\varphi_2 = -\frac{\nu_2}{\nu_1 - \nu_2} = 1{,}8453$$

Let us use the additional condition $r_2 = -r_3$;

$$R_1 = r_1 \cdot f'_{ob} = 569{,}3013\ mm$$

$$R_2 = r_2 \cdot f'_{ob} = 285{,}5124\ mm$$

$$R_3 = r_3 \cdot f'_{ob} = -569{,}3013\ mm$$

Determine the thicknesses.

14) Set the objective in Zemax Optic Studio software. Analyze the first-order properties, the layout, the spot diagrams, and the aberration plots.

Optimize the objective image quality: Correct the spherical aberration, the coma, the chromatic aberration, and control the focal length. The variables are the radii.

Table 7 – Lens Data of the objective

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
1				1,0000
2	316,352	8	N-SF5	1,6727
3	200,468	8	N-FK5	1,4875
4	-2708,748	707,985		1,0000

Table 8 – Cardinal points of the objective

f', mm	S_F, mm	$S'_{F'}$, mm	S_H, mm	$S'_{H'}$, mm
720,000	-721,862	707,984	-1,862	-12,015

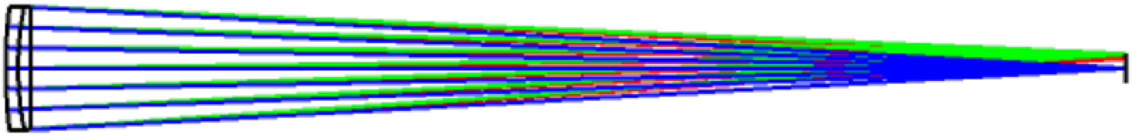


Figure 8 – Layout of the objective

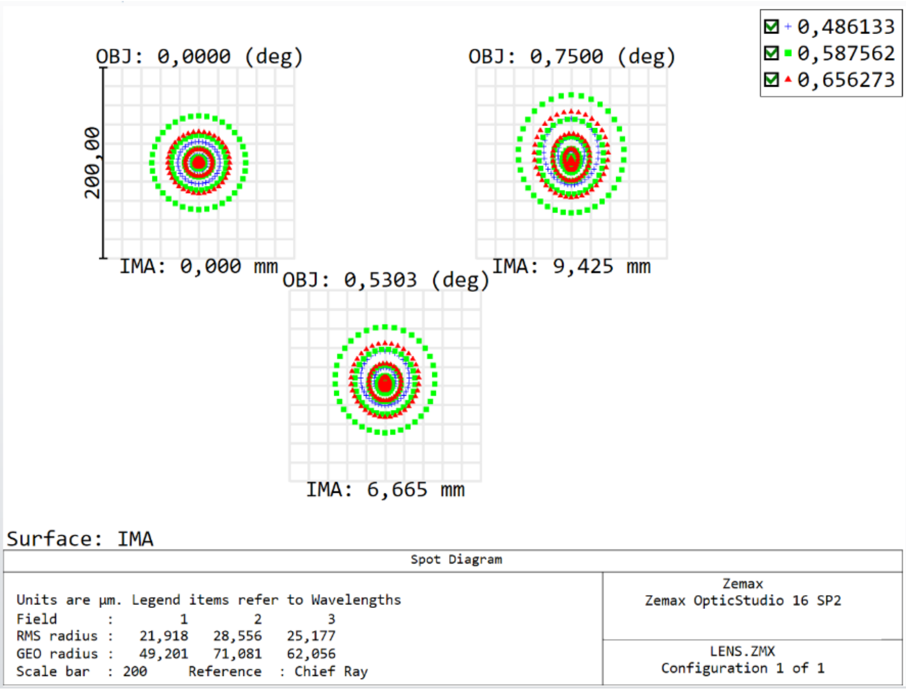


Figure 9 – Spot Diagram of the objective

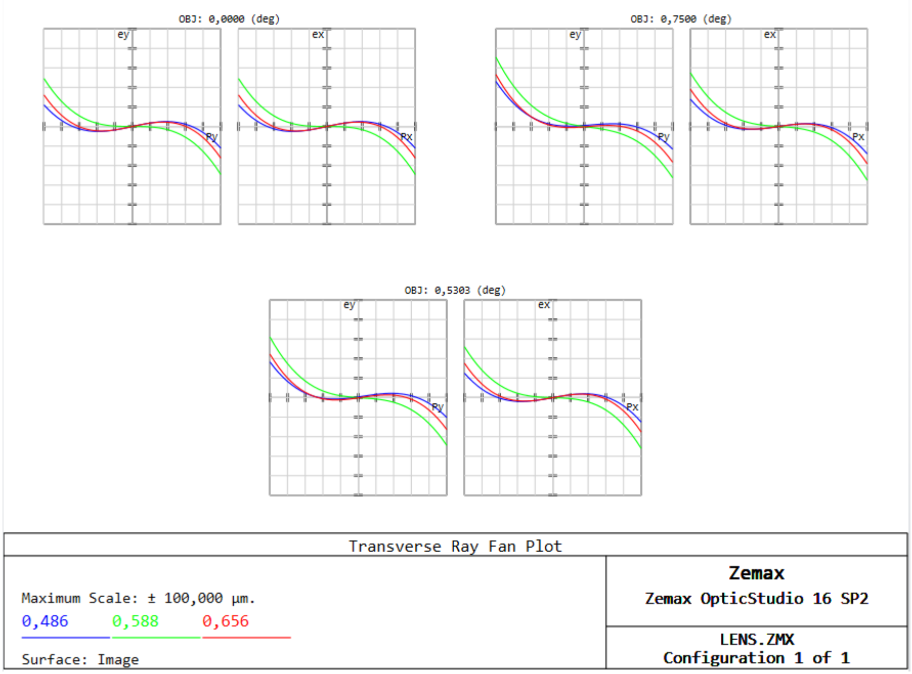


Figure 10 – Ray Fan Plot of the objective

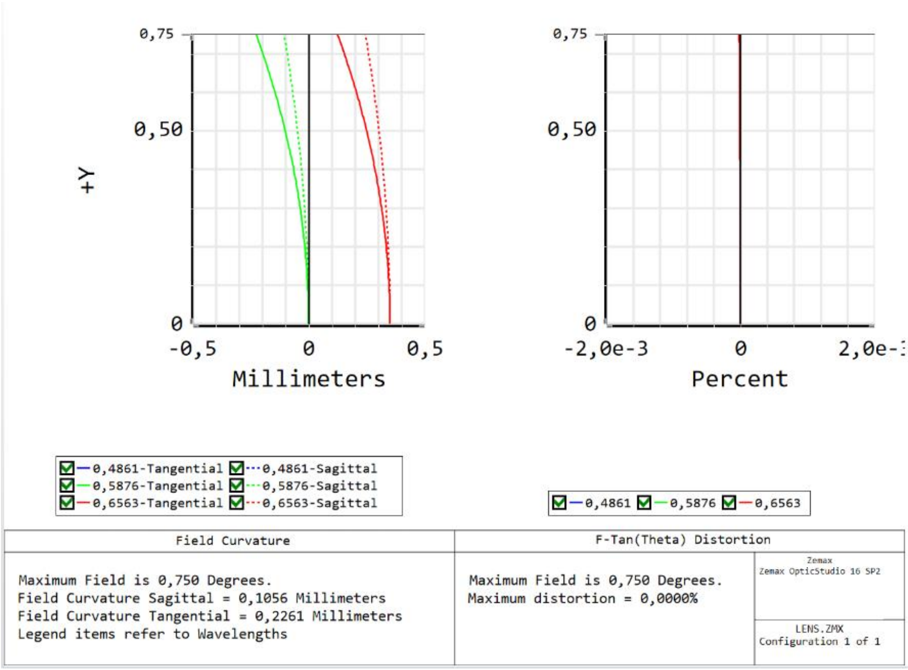


Figure 11 – Field curvature/distortion of the objective

Analyze the image quality of the objective:

The objective lens has an obvious spherical aberration in three fields of view, and the wavelengths of 0.486 and 0.666 are well corrected in terms of chromatic aberration.

15) Compose the system of the objective and the eye-piece, evaluate the image quality.

Switch on “afocal image space”.

Table 9 – Lens Data of the system

№	Radii	Thickness	Glasses	Index of refraction for the primary wavelength
1	infinity	Infinity		1.0000
2	316,352	8	N-SF5	1.6727
3	200,468	8	N-FK5	1.4875
4	-2708,748	707,985		1
5	infinity	17,087		1
6	-132,625	9,156	BK8	1.5202152
7	-36,189	0,343		
8	46,410	12,59	BK8	1.5202152
9	-31,817	3,434	LZ_TF4	1.740025
10	-159,452	0,343		
11	25,980	6,867	LZ_K8	1.51638
12	254,995	19,298		
STOP				

Table 10 – Cardinal points of the system

f', mm	s_F, mm	$s'_{F'}$, mm	s_H, mm	$s'_{H'}$, mm
infinity	infinity	infinity	infinity	infinity

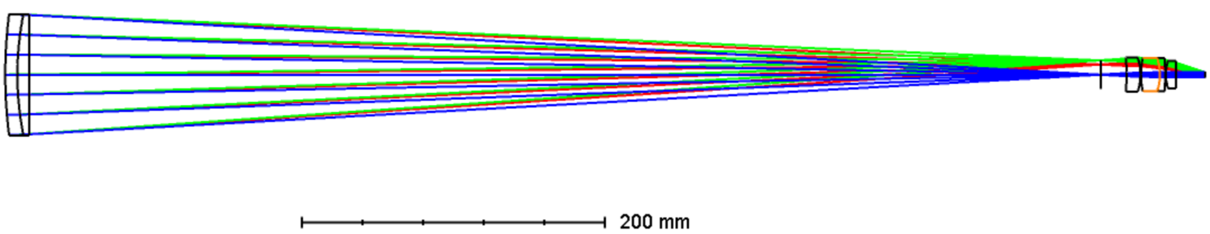


Figure 12 – Layout of the system

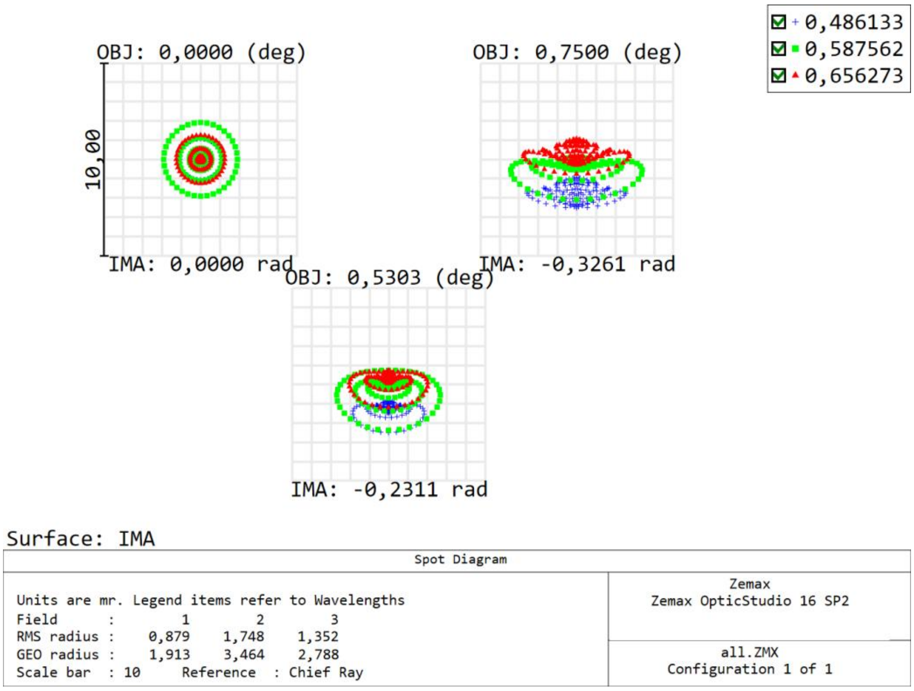


Figure 13 – Spot Diagram of the system

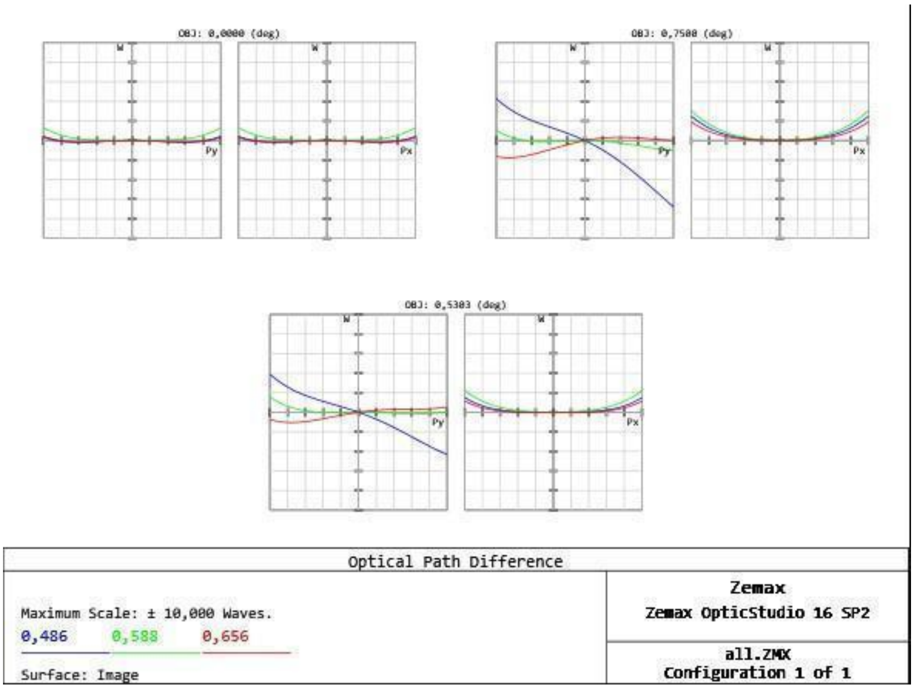


Figure 14 – Optical Path Difference of the system

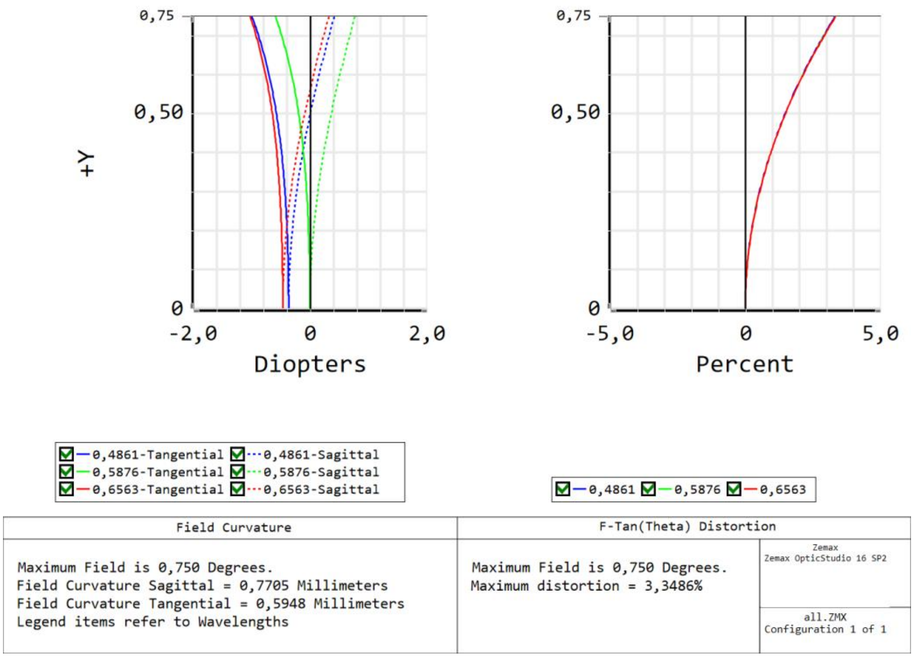


Figure 15 – Field curvature/distortion of the system

Analyze the image quality system:

After the objective and the eye-piece are spliced, the spherical difference of the three fields of view of the optical system is obvious, the vertical color difference is small in the 0 field of view, obvious in the 0,707 and 1 fields of view, and obvious in the three fields of view, the maximum values of the three wavelengths corresponding to 1 field of view are 0,544850, 1,799641, 0,899446, respectively.

16) Add a prism to reverse the image

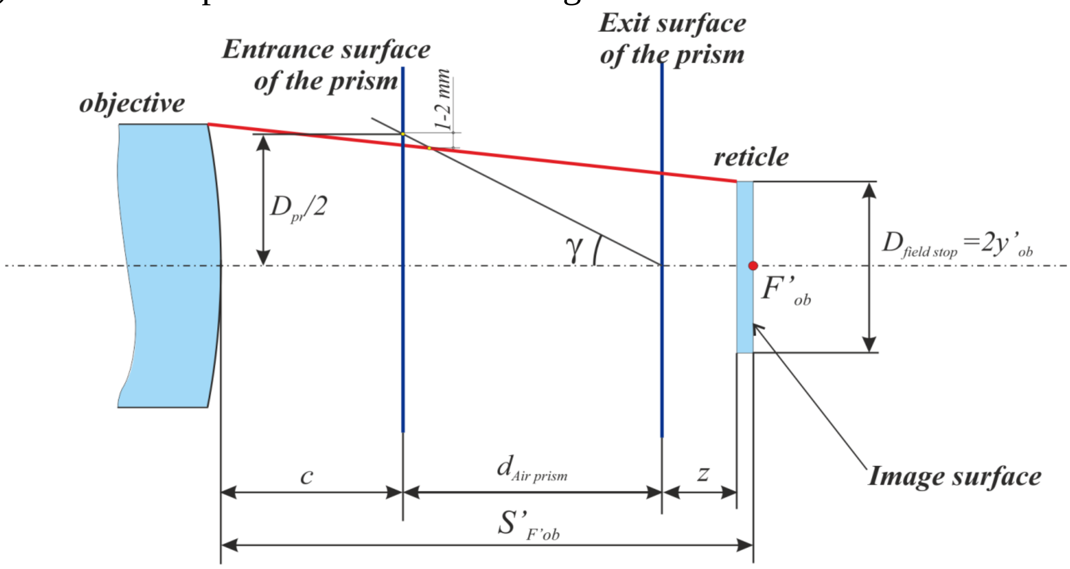


Figure 16 –Schematic drawing of inserting a prism into the optical system

Distance from the exit prisms surface to the intermediate image surface:

$$z \geq f'^2_2/100$$

$$tg\gamma = \frac{n}{2k}$$

k is the coefficient of the prism, for Porro system k=4;

Draw the components according to real ratios (the focal length, the distances, the diameters, the angle γ). From the drawing, we can get the value $D_{pr}/2$.

Ray path length for the prism:

$$d_{prism} = k \cdot D_{pr}$$

$$d_{air\ prism} = \frac{d_{prism}}{n}$$

Compare $d_{air\ prism}$ with the value in the drawing to check the calculations.

Choose the thickness of the reticle, for most cases it can be $d_{reticle} = 5\ mm$.

Calculate the equivalent air thickness:

$$d_{air\ reticle} = \frac{d_{reticle}}{n}$$

The distance from the objective to the entrance surface of the prism:

$$C = S'_{Fob} - d_{air\ reticle} - z - d_{air\ prism}$$

$$C = 656{,}611\ mm$$

$$D_{pr}/2 = 14{,}268\ mm$$

$$S'_{Fob} = 707{,}984\ mm$$

$$n = 1{,}50013\ mm$$

$$z = 10\ mm$$

$$d_{prism} = 57{,}073\ mm$$

$$d_{air\ prism} = 38{,}04\ mm$$

$$d_{air\ reticle} = 3{,}333\ mm$$

Table 10 – Lens Data of the telescope with a prism system

№	Radii	Thickness	Glasses	Semi-diameter
OBJ	infinity	Infinity		Infinity
STO	284,482	8	N-SF5	40,036
2	193,283	8	N-FK5	39,516
3	-2489,453	656,611		39,430
4	infinity	57,073	K11	11,587
5	infinity	10		9,976
6	infinity	5	K11	9,550
7	infinity	17,087		9,493
8	-132,625	9,16	BK8	10,407
9	-36,189	0,343		12,549
10	46,410	12,59	BK8	11,529
11	-31,817	3,43	LZ_TF4	10,298
12	-159,452	0,343		10,141
13	25,980	6,87	LZ_K8	9,090
14	254,995	19,398		7,087
IMA	infinity			3,218

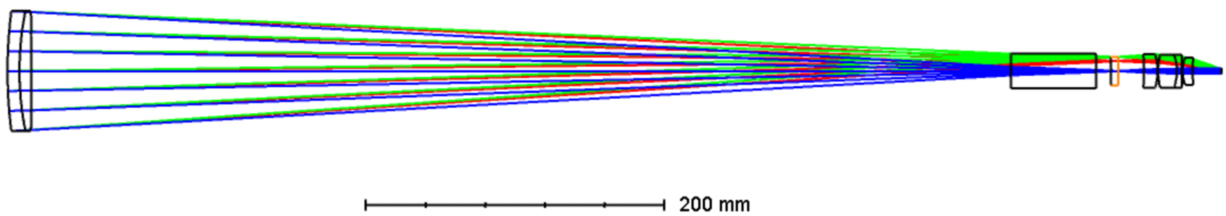


Figure 17 – Layout of the telescope with a prism system

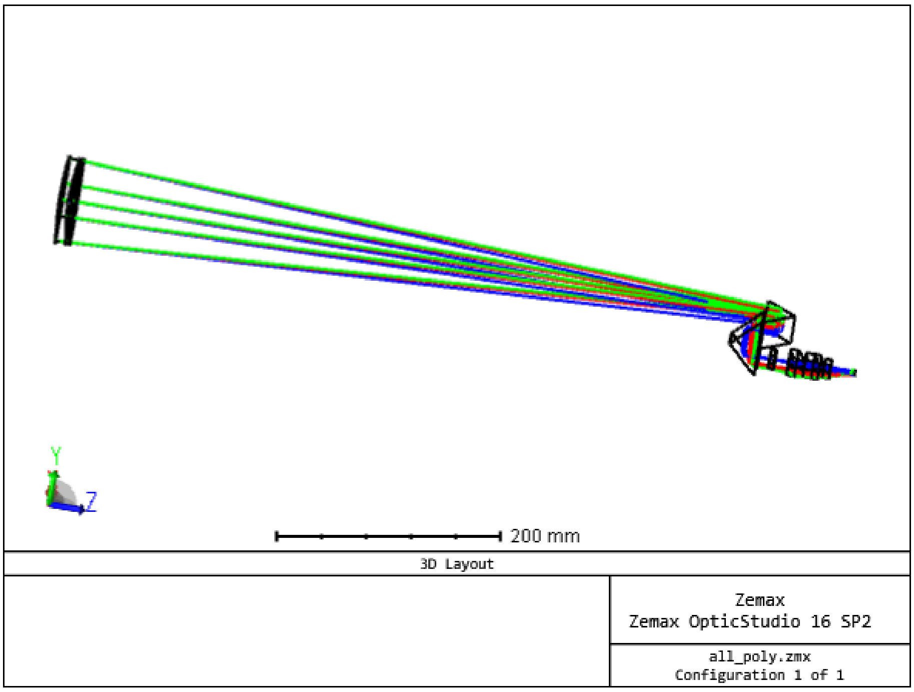


Figure 18 – 3D Layout of the telescope with a prism system (using Polygon Object)

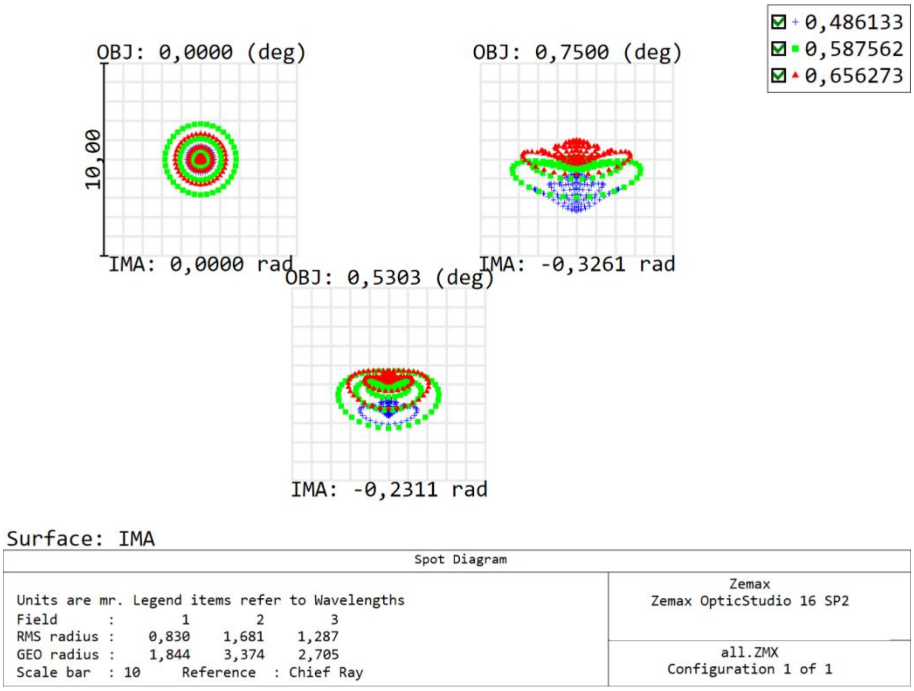


Figure 19 – Spot Diagram of the telescope with a prism system

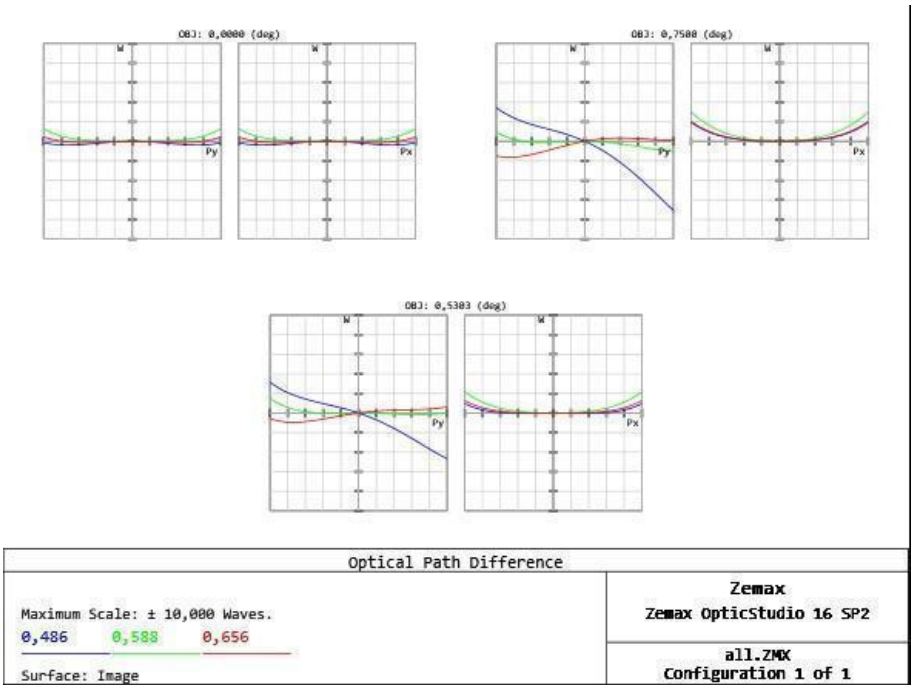


Figure 20 – Optical Path Difference of the telescope with a prism system

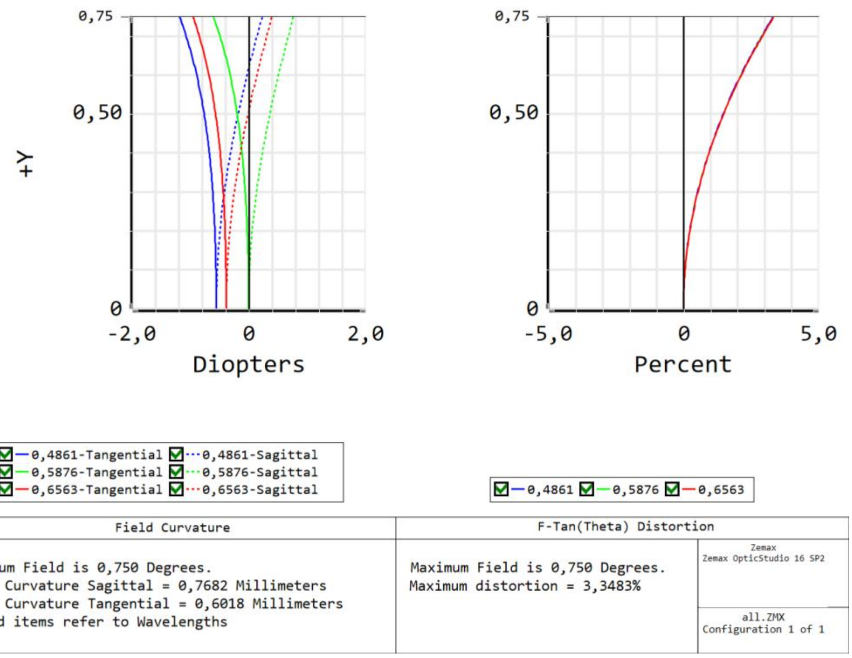


Figure 21 – Field curvature/distortion of the telescope with a prism system

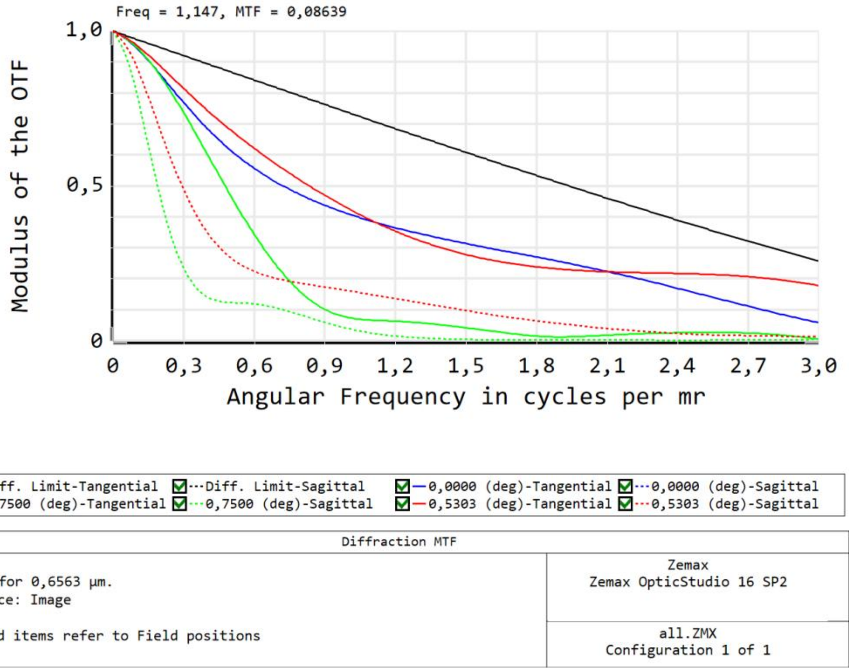


Figure 22 – MTF of the telescope with a prism system

Analyze the image quality system

When a prism and a reticle are added to the optical system, a serious chromatic aberration will appear. From SPT, it can be seen that the image quality of 0 field of view is good, but there is an obvious axial chromatic aberration in 0.707 and 1 fields of view. When people use the telescope, they usually focus on the center of vision, that is, the position of 0 field of view. Because the image quality of 0 field of view of the telescope is good, it basically meets the conditions of use.

References:

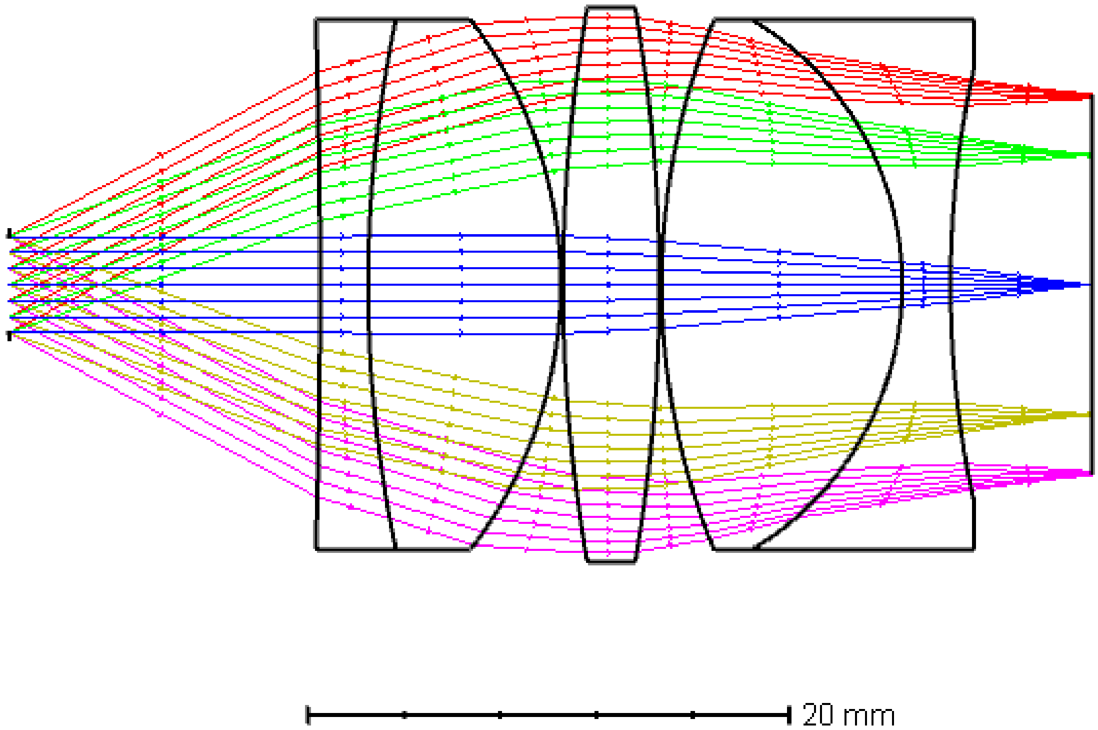
1. Malacara D. Handbook of Optical Design. – Marcel Dekker, Inc. 2004
2. R.N Wilson Reflecting Telescope Optics I: Basic Design Theory and its Historical Development 2004
3. Warren J. Smith Modern Lens Design – McGraw-Hill, 1992
4. Paul R. Yoder, Jr., Daniel Vukobratovich Field Guide Binoculars and Scopes. SPIE Press, Bellingham, 2011.
5. Warren J. Smith Modern Optical Engineering. 3d edition – McGraw-Hill, 2000
6. Naftaly Menn Practical Optics- Elsevir Academic Press. - 2004
7. Schoeder D.J. Astronomical Optics 2^{nd} Edition, 2000
8. Robert E. Fischer; Biljana Tadic-Galeb; Paul R. Yoder Jr. Optical Systems Design. – SPIE Press, 2008
9. Haiyin Sun Lens Design: A Practical Guide. – CRC Press, 2017
10. Harrie G J Rutten, Martin A M van Venrooij, Richard Berry, Diane Lucas Telescope Optic Evaluation and Design. – Willman-Bell 1988
11. Michael Kidger Fundamental Optical Design. – SPIE Press
12. Bruce H. Walker Optical Design for Visual Systems 2000

Appendix A
Eye-pieces

Lens data for eye-pieces are given in reverse ray paths (for the object in infinity)
Pay attention to the glass catalog used

1. Erfle eye-piece $f' = 15.6$, $D = 4$ mm, $2\omega = 56°$

5 lenses, focal length $f' = 15.6071$, pupil diameter $D = 4$ mm, full angular field $2\omega = 56°$, pupil position 12.93 with respect to the lens



GENERAL LENS DATA:

Surfaces	:	10
Stop	:	1
System Aperture	:	Entrance Pupil Diameter = 4
Glass Catalogs	:	LZOS
Effective Focal Length	:	15,60681 (in image space)
Back Focal Length	:	5,93863
Image Space F/#	:	3,901702
Image Space NA	:	0,1271097
Stop Radius	:	2
Paraxial Image Height	:	8,298286
Entrance Pupil Diameter	:	4
Field Type	:	Angle in degrees
Maximum Radial Field	:	28
Primary Wavelength [µm]	:	0,546074

Wavelengths : 3
Units: µm

#	Value	Weight
1	0,479991	1,000000
2	0,546074	1,000000
3	0,643847	1,000000

SURFACE DATA SUMMARY:

Surf	**Type**	**Radius**	**Thickness**	**Glass**	**Clear Diam**	**Conic**	**Comment**
OBJ	STANDARD	Infinity	Infinity		0	0	
STO	STANDARD	Infinity	12,93		4	0	pupil
2	STANDARD	-340,4	2	LZ_TF4	17,63	0	
3	STANDARD	52,97	8	LZ_CTK3	19,40	0	
4	STANDARD	-17,989	0,1		21,64	0	
5	STANDARD	66,07	4	LZ_CTK3	22,28	0	
6	STANDARD	-66,07	0,1		22,17	0	
7	STANDARD	28,91	10	LZ_CTK3	21,20	0	
8	STANDARD	-12,794	2	LZ_TF4	19,45	0	
9	STANDARD	41,88	5,89		17,04	0	
IMA	STANDARD	Infinity			15,80	0	

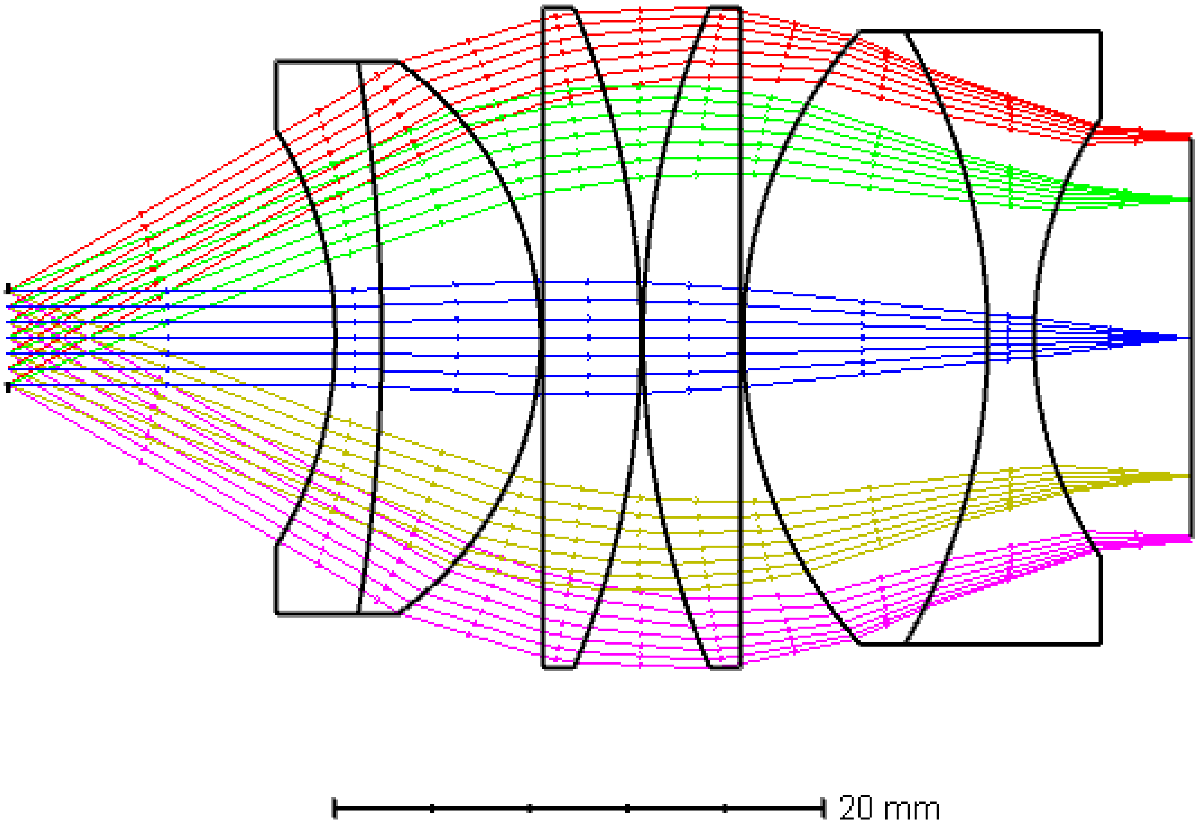
CARDINAL POINTS:
Object space positions are measured with respect to surface 2.
Image space positions are measured with respect to surface 9.
The index in both the object space and image space is considered.

W = 0,546074(Primary)

	Object Space	**Image Space**
Focal Length :	-15,606807	15,606807
Focal Planes :	-11,456549	5,938630
Principal Planes :	4,150258	-9,668177
Anti-Principal Planes :	-27,063356	21,545437
Nodal Planes :	4,150258	-9,668177
Anti-Nodal Planes :	-27,063356	21,545437

2. Eye-piece SOI (designed at S.I.Vavilov State Optical Institute) *f* ′= 15.2, *D* = 3.8 mm, 2ω = 60°

6 lenses, focal length *f* ′ = 15.23, pupil diameter *D* = 3,8 mm, full angular field 2ω = 60°, pupil position 13.4 with respect to the lens.




```
GENERAL LENS DATA:

Surfaces                    :                  12
Stop                        :                   1
System Aperture             :   Entrance Pupil Diameter =   3,8
Glass Catalogs              :   LZOS
Effective Focal Length      :           15,22743 (in image space)
Back Focal Length           :           6,437559
Image Space F/#             :           4,007218
Image Space NA              :          0,1238148
Stop Radius                 :                1,9
Paraxial Image Height       :           8,791559
Entrance Pupil Diameter     :                3,8
Field Type                  :   Angle in degrees
Maximum Radial Field        :                 30
Primary Wavelength [µm]     :           0,546074

Fields             : 3
Field Type                  :   Angle in degrees
 #        X-Value          Y-Value            Weight
 1          0,000000         0,000000           1,000000
 2          0,000000        21,210000           1,000000
```

3	0,000000	30,000000	1,000000

Wavelengths : 3
Units: µm

#	Value	Weight
1	0,479991	1,000000
2	0,546074	1,000000
3	0,643847	1,000000

SURFACE DATA SUMMARY:

Surf	Type	Radius	Thickness	Glass	Clear Diam	Conic	Comment
OBJ	STANDARD	Infinity	Infinity		0	0	
STO	STANDARD	Infinity	13,4		3,8	0	pupil
2	STANDARD	-16,19	1,9	LZ_TF4	16,62	0	
3	STANDARD	-66,37	6,5	LZ_TK16	20,60	0	
4	STANDARD	-13,804	0,1		22,50	0	
5	STANDARD	Infinity	4	LZ_TK16	26,05	0	
6	STANDARD	-34,67	0,1		26,54	0	
7	STANDARD	34,67	4	LZ_TK16	26,99	0	
8	STANDARD	Infinity	0,1		26,66	0	
9	STANDARD	18,793	10	LZ_TK16	24,66	0	
10	STANDARD	-24,77	1,9	LZ_TF4	22,27	0	
11	STANDARD	16,19	6,44		17,44	0	
IMA	STANDARD	Infinity			16,35	0	

CARDINAL POINTS:

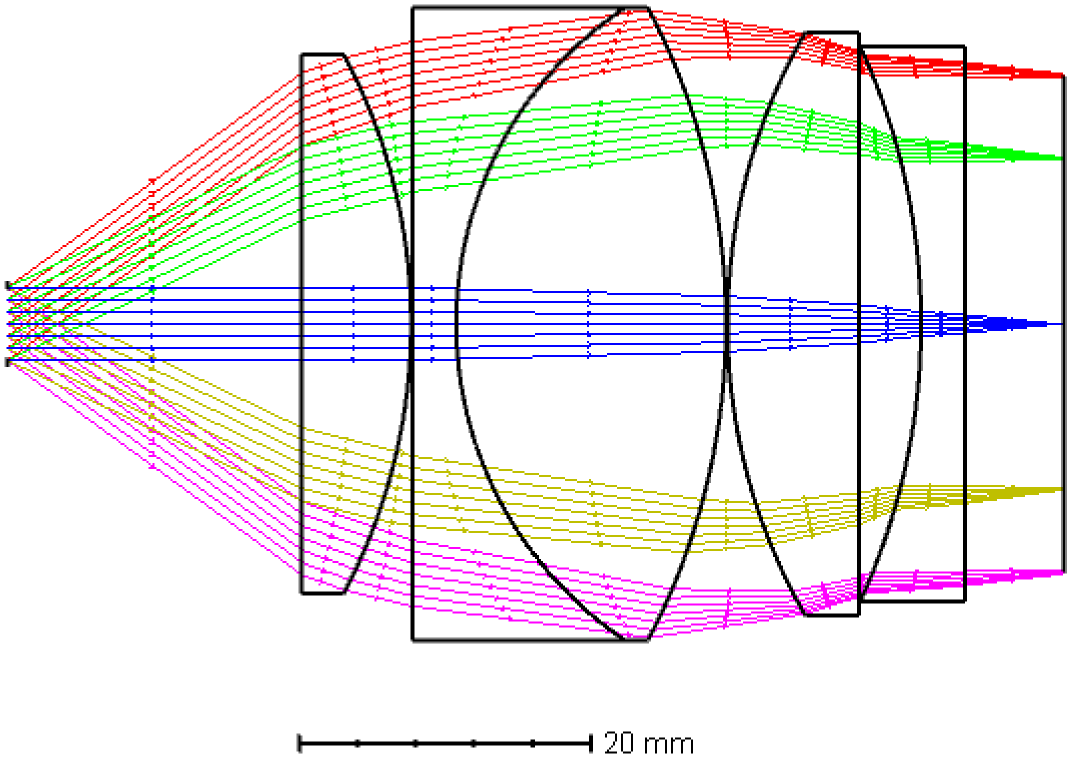
Object space positions are measured with respect to surface 2.
Image space positions are measured with respect to surface 11.
The index in both the object space and image space is considered.

W = 0,546074 (Primary)

	Object Space	Image Space
Focal Length :	-15,227427	15,227427
Focal Planes :	-11,678261	6,437559
Principal Planes :	3,549166	-8,789868
Anti-Principal Planes :	-26,905689	21,664987
Nodal Planes :	3,549166	-8,789868
Anti-Nodal Planes :	-26,905689	21,664987

3. Eye-piece of M.M.Rusinov $f' = 25$, $D = 5$ mm, $2\omega = 72°$

5 lenses, focal length $f' = 24.88$, pupil diameter $D = 5$ mm, full angular field $2\omega = 72°$, pupil position 20.23 with respect to the lens.




```
GENERAL LENS DATA:

Surfaces                     :                 11
Stop                         :                  1
System Aperture              :  Entrance Pupil Diameter =   5
Glass Catalogs               :  LZOS
Effective Focal Length       :          24,97408 (in image space)
Back Focal Length            :          6,530217
Image Space F/#              :          4,994816
Image Space NA               :        0,09960598
Stop Radius                  :               2,5
Paraxial Image Height        :          18,14473
Entrance Pupil Diameter      :                 5
Field Type                   :  Angle in degrees
Maximum Radial Field         :                36
Primary Wavelength [µm]      :          0,546074

Fields           : 3
Field Type                   :  Angle in degrees
 #        X-Value            Y-Value           Weight
 1          0,000000          0,000000          1,000000
 2          0,000000         25,452000          1,000000
 3          0,000000         36,000000          1,000000
```

Wavelengths : 3
Units: µm

#	Value	Weight
1	0,479991	1,000000
2	0,546074	1,000000
3	0,643847	1,000000

SURFACE DATA SUMMARY:

Surf	Type	Radius	Thickness	Glass	Clear Diam	Conic	Comment
OBJ	STANDARD	Infinity	Infinity		0	0	
STO	STANDARD	Infinity	20,23		5	0	pupil
2	STANDARD	Infinity	7,5	LZ_CTK9	34,40	0	
3	STANDARD	-39,142	0,1		36,53	0	
4	STANDARD	Infinity	3	LZ_TF4	38,79	0	
5	STANDARD	26,112	18,5	LZ_CTK9	42,67	0	
6	STANDARD	-46,484	0,1		43,23	0	
7	STANDARD	40,002	9	LZ_CTK9	39,78	0	
8	STANDARD	Infinity	4,3		37,39	0	
9	STANDARD	-45,25	3	LZ_TF4	36,92	0	
10	STANDARD	Infinity	6,83		35,89	0	
IMA	STANDARD	Infinity			34,08	0	

CARDINAL POINTS:

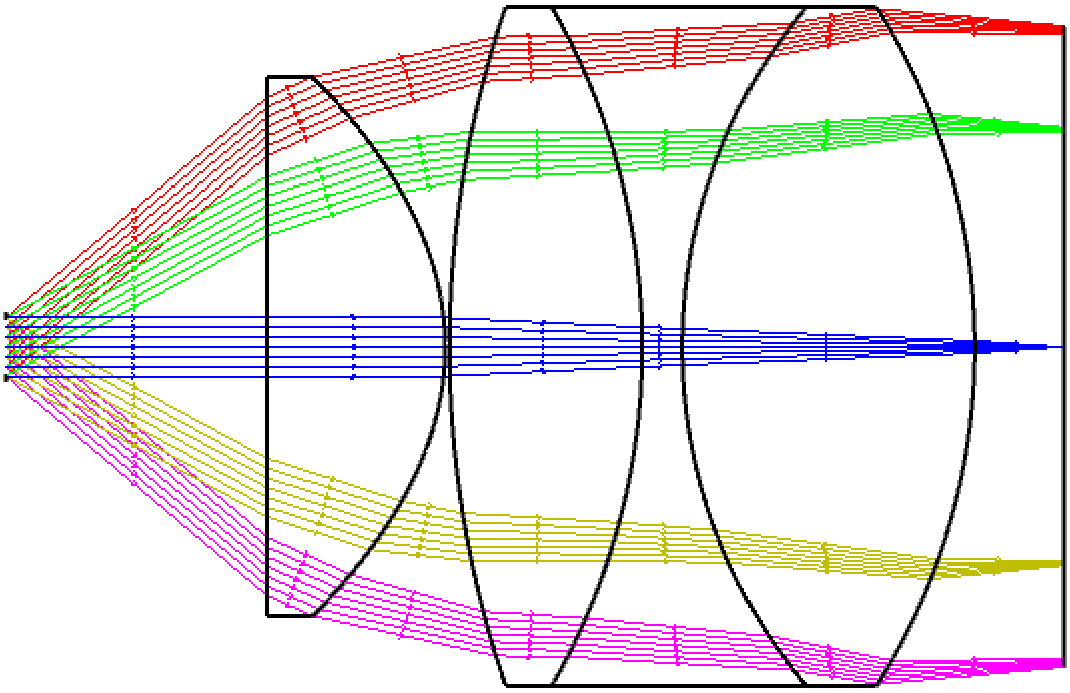
Object space positions are measured with respect to surface 2.
Image space positions are measured with respect to surface 10.
The index in both the object space and image space is considered.

W = 0,546074 (Primary)e

	Object Space	Image Space
Focal Length :	-24,974078	24,974078
Focal Planes :	-17,240461	6,530217
Principal Planes :	7,733617	-18,443861
Anti-Principal Planes :	-42,214539	31,504294
Nodal Planes :	7,733617	-18,443861
Anti-Nodal Planes :	-42,214539	31,504294

4. Eye-piece with an aspherical surface $f' = 25$, $D = 3.5$, $2\omega = 80°$

4 lenses, focal length $f' = 25.055$, pupil diameter $D = 3.52$, full angular field $2\omega = 80°$, pupil position 15.73 with respect to the lens.




```
GENERAL LENS DATA:

Surfaces                   :                 8
Stop                       :                 1
System Aperture            :   Entrance Pupil Diameter =   3,52
Glass Catalogs             :   LZOS
Effective Focal Length     :         25,05412 (in image space)
Back Focal Length          :         5,383695
Image Space F/#            :         7,117649
Image Space NA             :       0,07007523
Stop Radius                :             1,76
Paraxial Image Height      :         21,02291
Entrance Pupil Diameter    :             3,52
Field Type                 :   Angle in degrees
Maximum Radial Field       :               40
Primary Wavelength [μm]    :         0,546074


Fields          : 3
Field Type                 :   Angle in degrees
 #        X-Value          Y-Value          Weight
 1        0,000000         0,000000        1,000000
 2        0,000000        28,280000        1,000000
 3        0,000000        40,000000        1,000000
```

Wavelengths : 3
Units: µm

#	Value	Weight
1	0,479991	1,000000
2	0,546074	1,000000
3	0,643847	1,000000

SURFACE DATA SUMMARY:

Surf	Type	Radius	Thickness	Glass	Clear Diam	Conic	Comment
OBJ	STANDARD	Infinity	Infinity		0	0	
STO	STANDARD	Infinity	15,73		3,52	0	pupil
2	STANDARD	Infinity	10,68	LZ_BK8	29,92	0	
3	STANDARD	-16,43	0,26		32,39	-1	Paraboloid
4	STANDARD	63,096	11,61	LZ_TK23	37,38	0	
5	STANDARD	-40,876	2,41	LZ_TF4	37,55	0	
6	STANDARD	31,794	17,54	LZ_BK10	39,21	0	
7	STANDARD	-38,086	5,39		40,78	0	
IMA	STANDARD	Infinity			38,51	0	

CARDINAL POINTS:

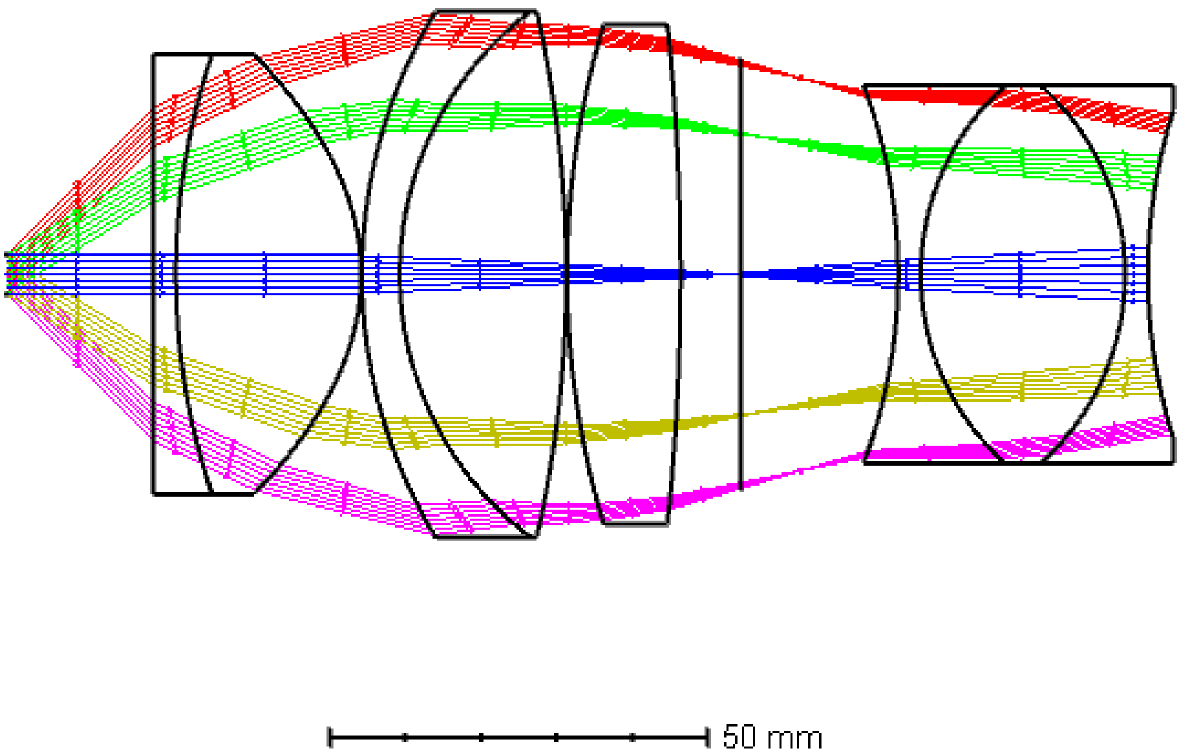
Object space positions are measured with respect to surface 2.
Image space positions are measured with respect to surface 7.
The index in both the object space and image space is considered.

W = 0,546074 (Primary)

	Object Space	**Image Space**
Focal Length :	-25,054124	25,054124
Focal Planes :	-12,170430	5,383695
Principal Planes :	12,883694	-19,670430
Anti-Principal Planes :	-37,224555	30,437819
Nodal Planes :	12,883694	-19,670430
Anti-Nodal Planes :	-37,224555	30,437819

5. Wide angle eye-piece $f' = 25$, $D = 5$ mm, $2\omega = 90°$

8 lenses, focal length $f' = 25$, pupil diameter $D = 5$ mm, full field of view $2\omega = 90°$, pupil position 19.41 with respect to the lens.




```
GENERAL LENS DATA:

Surfaces                    :                 15
Stop                        :                  1
System Aperture             :  Entrance Pupil Diameter =   5
Glass Catalogs              :  LZOS
Effective Focal Length      :           24,99789 (in image space)
Back Focal Length           :          -35,00905
Image Space F/#             :           4,999578
Image Space NA              :         0,09951203
Stop Radius                 :                2,5
Paraxial Image Height       :           24,99789
Entrance Pupil Diameter     :                  5
Field Type                  :  Angle in degrees
Maximum Radial Field        :                 45
Primary Wavelength [µm]     :           0,546074

Fields          : 3
Field Type                  :  Angle in degrees
 #       X-Value          Y-Value          Weight
 1          0,000000         0,000000         1,000000
 2          0,000000        31,815000         1,000000
 3          0,000000        45,000000         1,000000
```

Wavelengths : 3
Units: µm

#	Value	Weight
1	0,479991	1,000000
2	0,546074	1,000000
3	0,643847	1,000000

SURFACE DATA SUMMARY:

Surf	Type	Radius	Thickness	Glass	Clear Diam	Conic	Comment
OBJ	STANDARD	Infinity	Infinity		0	0	
STO	STANDARD	Infinity	19,41		5	0	pupil
2	STANDARD	Infinity	3	LZ_F1	43,82	0	
3	STANDARD	90,16	24,5	LZ_TK16	50,25	0	
4	STANDARD	-29,64	0,1		57,21	-1	Paraboloid
5	STANDARD	66,68	5	LZ_TF4	69,18	0	
6	STANDARD	43,45	22	LZ_K8	66,54	0	
7	STANDARD	-155,6	0,1		66,67	0	
8	STANDARD	114,55	15	LZ_K8	65,36	0	
9	STANDARD	-314,1	8		62,75	0	
10	STANDARD	Infinity	20,75		57,17	0	
11	STANDARD	-70,47	3	LZ_K8	49,21	0	
12	STANDARD	33,42	27	LZ_F4	49,37	0	
13	STANDARD	-33,42	3	LZ_K8	48,64	0	
14	STANDARD	70,47	-35		43,36	0	
IMA	STANDARD	Infinity			49,00	0	

CARDINAL POINTS:

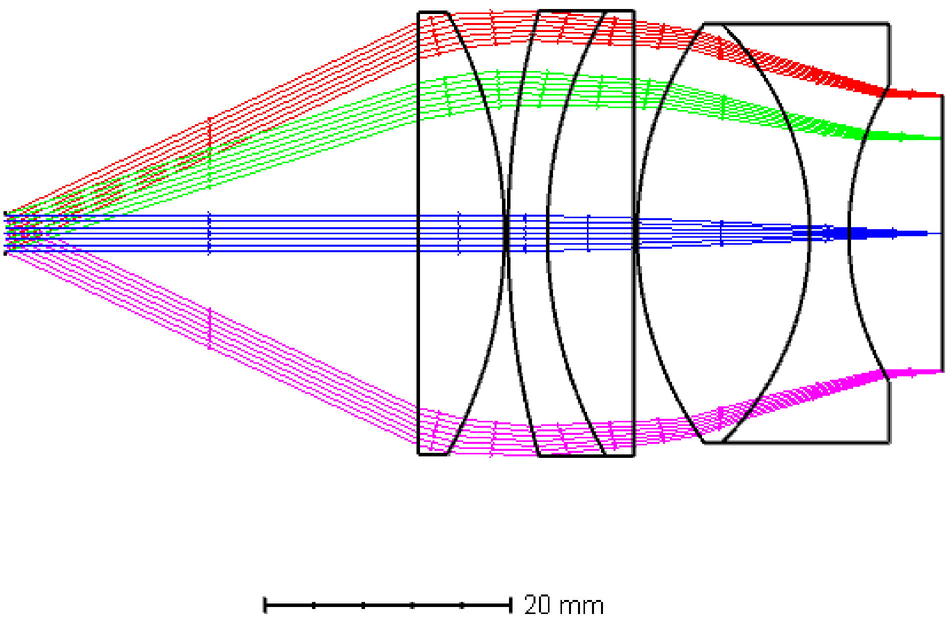
Object space positions are measured with respect to surface 2.
Image space positions are measured with respect to surface 14.
The index in both the object space and image space is considered.

W = 0,546074 (Primary)

	Object Space	**Image Space**
Focal Length :	-24,997890	24,997890
Focal Planes :	-16,034054	-35,009048
Principal Planes :	8,963836	-60,006938
Anti-Principal Planes :	-41,031944	-10,011157
Nodal Planes :	8,963836	-60,006938
Anti-Nodal Planes :	-41,031944	-10,011157

6. Eye-piece with a large eye relief $f' = 25$, $D = 3$ mm, $2\omega = 50°$

5 lenses, focal length $f' = 25.065$, pupil diameter $D = 3$ mm, full angular field $2\omega = 50°$, pupil position 33.57 with respect to the lens.



GENERAL LENS DATA:

Surfaces : 10
Stop : 1
System Aperture : Entrance Pupil Diameter = 3
Glass Catalogs : LZOS
Effective Focal Length : 25,06435 (in image space)
Back Focal Length : 7,607925
Image Space F/# : 8,354783
Image Space NA : 0,05973907
Stop Radius : 1,5
Paraxial Image Height : 11,6877
Entrance Pupil Diameter : 3
Field Type : Angle in degrees
Maximum Radial Field : 25
Primary Wavelength [µm] : 0,546074

Fields : 3
Field Type : Angle in degrees

#	X-Value	Y-Value	Weight
1	0,000000	0,000000	1,000000
2	0,000000	17,675000	1,000000
3	0,000000	25,000000	1,000000

Wavelengths : 3
Units: µm

#	Value	Weight
1	0,479991	1,000000
2	0,546074	1,000000

3 0,643847 1,000000

SURFACE DATA SUMMARY:

Surf	Type	Radius	Thickness	Glass	Clear Diam	Conic	Comment
OBJ	STANDARD	Infinity	Infinity		0	0	
STO	STANDARD	Infinity	33,57		3	0	pupil
2	STANDARD	Infinity	7	LZ_CTK19	34,31	0	
3	STANDARD	-36,98	0,3		35,54	0	
4	STANDARD	65,77	3,2	LZ_TF10	36,20	0	
5	STANDARD	36,64	7	LZ_CTK19	35,16	0	
6	STANDARD	Infinity	0,3		34,72	0	
7	STANDARD	29,24	14	LZ_CTK19	33,07	0	
8	STANDARD	-23,77	3,2	LZ_TF10	30,70	0	
9	STANDARD	23,77	7,61		23,47	0	
IMA	STANDARD	Infinity			22,53	0	

CARDINAL POINTS:

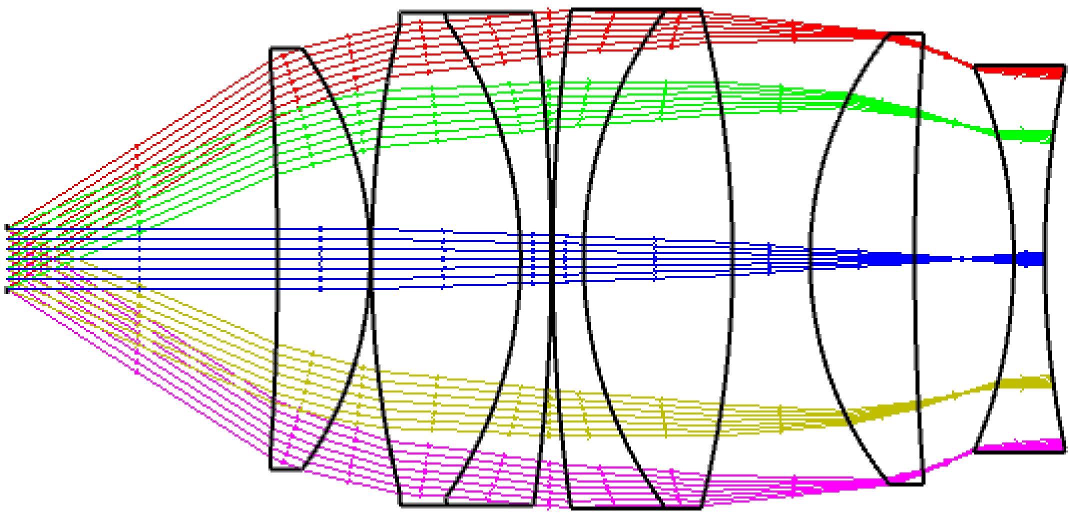
Object space positions are measured with respect to surface 2.
Image space positions are measured with respect to surface 9.
The index in both the object space and image space is considered.

W = 0,546074 (Primary)

	Object Space	**Image Space**
Focal Length :	-25,064350	25,064350
Focal Planes :	-30,430598	7,607925
Principal Planes :	-5,366248	-17,456425
Anti-Principal Planes :	-55,494948	32,672275
Nodal Planes :	-5,366248	-17,456425
Anti-Nodal Planes :	-55,494948	32,672275

7. Eye-piece $f' = 25$, $D = 5$ mm, $2\omega = 65°$

7 lenses, focal length $f' = 25.065$, pupil diameter $D = 5$ mm, full angular field $2\omega = 65°$, pupil position 22.74 with respect to the lens.




```
GENERAL LENS DATA:

Surfaces                  :                  14
Stop                      :                   1
System Aperture           :    Entrance Pupil Diameter =    5
Glass Catalogs            :    LZOS
Effective Focal Length    :            24,96573  (in image space)
Back Focal Length         :           -5,412659
Total Track               :               87,14
Image Space F/#           :            4,993146
Image Space NA            :          0,09963895
Stop Radius               :                 2,5
Paraxial Image Height     :            15,90492
Entrance Pupil Diameter   :                   5
Field Type                :    Angle in degrees
Maximum Radial Field      :                32,5
Primary Wavelength [µm]   :            0,546074

Fields           : 3
Field Type                :    Angle in degrees
 #       X-Value          Y-Value            Weight
 1          0,000000         0,000000          1,000000
 2          0,000000        22,977500          1,000000
 3          0,000000        32,500000          1,000000
```

Wavelengths : 3
Units: µm

#	Value	Weight
1	0,479991	1,000000
2	0,546074	1,000000
3	0,643847	1,000000

SURFACE DATA SUMMARY:

Surf	Type	Radius	Thickness	Glass	Clear Diam	Conic	Comment
OBJ	STANDARD	Infinity	Infinity			0	
STO	STANDARD	Infinity	22,74		5	0	pupil
2	STANDARD	-226,5	7,8	LZ_BK8	33,20	0	
3	STANDARD	-30,06	0,1		35,36	0	
4	STANDARD	82,79	12,5	LZ_TK16	39,52	0	
5	STANDARD	-35	2,6	LZ_TF4	39,94	0	
6	STANDARD	-142,23	0,1		41,38	0	
7	STANDARD	142,23	,6	LZ_TF4	41,78	0	
8	STANDARD	35	12,5	LZ_TK16	41,36	0	
9	STANDARD	-82,79	6,5		41,53	0	
10	STANDARD	30,06	8,8	LZ_BK8	37,89	0	
11	STANDARD	226,5	8,3		36,00	0	
12	STANDARD	-40,46	2,6	LZ_BK10	32,42	0	
13	STANDARD	74,82	-5,41		31,87	0	
IMA	STANDARD	Infinity			30,91		

CARDINAL POINTS:

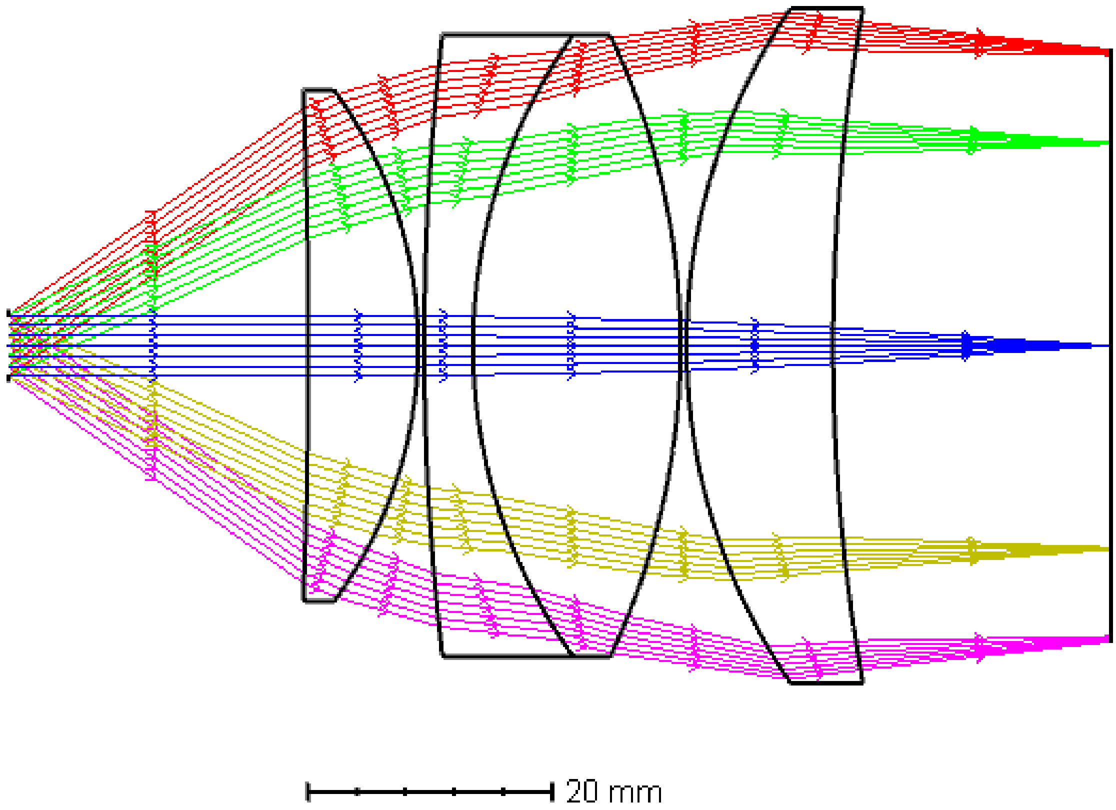
Object space positions are measured with respect to surface 2.
Image space positions are measured with respect to surface 13.
The index in both the object space and image space is considered.

W = 0,546074 (Primary)

	Object Space	**Image Space**
Focal Length :	-24,965729	24,965729
Focal Planes :	-22,760171	-5,412659
Principal Planes :	2,205558	-30,378388
Anti-Principal Planes :	-47,725900	19,553071
Nodal Planes :	2,205558	-30,378388
Anti-Nodal Planes :	-47,725900	19,553071

8. Eye-piece $f' = 38$, $D = 5$ mm, $2\omega = 70°$

4 lenses, focal length $f' = 38.44$, pupil diameter $D = 5$ mm, full angular field $2\omega = 70°$, pupil position 24.6 with respect to the lens.




```
GENERAL LENS DATA:

Surfaces                   :                   9
Stop                       :                   1
System Aperture            :    Entrance Pupil Diameter =    5
Glass Catalogs             :    LZOS
Effective Focal Length     :            38,44622  (in image space)
Back Focal Length          :             22,7705
Image Space F/#            :            7,689244
Image Space NA             :          0,06488886
Stop Radius                :                 2,5
Paraxial Image Height      :            26,92033
Entrance Pupil Diameter    :                   5
Field Type                 :    Angle in degrees
Maximum Radial Field       :                  35
Primary Wavelength [µm]    :            0,546074

Fields          : 3
Field Type                 :    Angle in degrees
 #        X-Value            Y-Value            Weight
 1         0,000000          0,000000          1,000000
 2         0,000000         24,745000          1,000000
 3         0,000000         35,000000          1,000000
```

Wavelengths : 3
Units: µm

#	Value	Weight
1	0,479991	1,000000
2	0,546074	1,000000
3	0,643847	1,000000

SURFACE DATA SUMMARY:

Surf	Type	Radius	Thickness	Glass	Clear Diam	Conic	Comment
OBJ	STANDARD	Infinity	Infinity		0	0	
STO	STANDARD	Infinity	24,6		5	0	pupil
2	STANDARD	-535,5	9	LZ_K8	38,95	0	
3	STANDARD	-35,32	0,5		41,26	0	
4	STANDARD	218,8	4	LZ_TF4	46,19	0	
5	STANDARD	43,65	17	LZ_K8	48,57	0	
6	STANDARD	-59,16	0,5		50,57	0	
7	STANDARD	49,2	12	LZ_K8	54,83	0	
8	STANDARD	157,04	22,77		53,27	0	
IMA	STANDARD	Infinity			48,70	0	

CARDINAL POINTS:

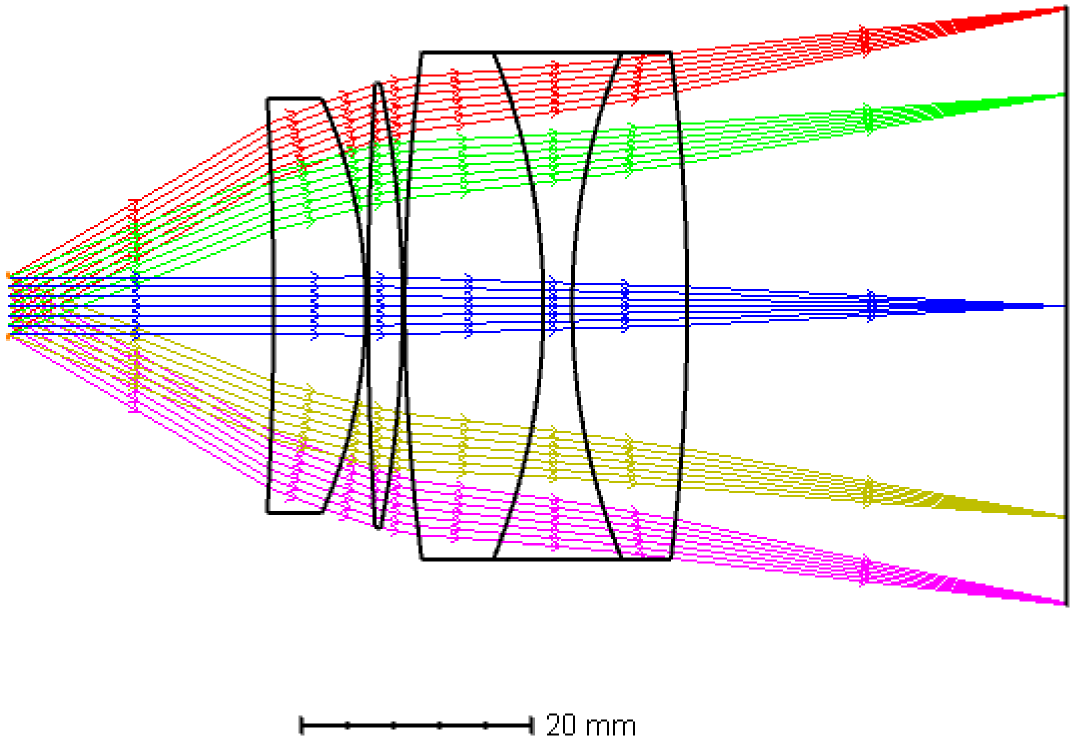
Object space positions are measured with respect to surface 2.
Image space positions are measured with respect to surface 8.
The index in both the object space and image space is considered.

W = 0,546074 (Primary)

	Object Space	Image Space
Focal Length :	-38,446220	38,446220
Focal Planes :	-24,796622	22,770497
Principal Planes :	13,649598	-15,675724
Anti-Principal Planes :	-63,242843	61,216717
Nodal Planes :	13,649598	-15,675724
Anti-Nodal Planes :	-63,242843	61,216717

9. Eye-piece $f' = 49$, $D = 5$ mm, $2\omega = 61°$

5 lenses, focal length $f' = 49.09$, pupil diameter $D = 5$ mm, full angular field $2\omega = 61°$, pupil position 23 mm with respect to the lens.




```
GENERAL LENS DATA:

Surfaces                    :                  10
Stop                        :                   1
System Aperture             :    Entrance Pupil Diameter =    5
Glass Catalogs              :    LZOS
Effective Focal Length      :            49,09231 (in image space)
Back Focal Length           :            32,90674
Image Space F/#             :            9,818463
Image Space NA              :          0,05085857
Stop Radius                 :                 2,5
Paraxial Image Height       :            28,91758
Entrance Pupil Diameter     :                   5
Field Type                  :    Angle in degrees
Maximum Radial Field        :                30,5
Primary Wavelength [µm]     :            0,546074

Fields            : 3
Field Type                  :    Angle in degrees
 #        X-Value          Y-Value             Weight
 1           0,000000         0,000000            1,000000
 2           0,000000        21,563500            1,000000
 3           0,000000        30,500000            1,000000

Wavelengths       : 3
Units: µm
 #           Value            Weight
 1           0,479991         1,000000
```

2 0,546074 1,000000
3 0,643847 1,000000

SURFACE DATA SUMMARY:

Surf	**Type**	**Radius**	**Thickness**	**Glass**	**Clear Diam**	**Conic**	**Comment**
OBJ	STANDARD	Infinity	Infinity		0	0	
STO	STANDARD	Infinity	23		5	0	pupil
2	STANDARD	-288,4	8	LZ_K8	31,59	0	
3	STANDARD	-44,38	0,2		35,22	0	
4	STANDARD	299,2	3	LZ_BK8	38,38	0	
5	STANDARD	-98,18	0,2		38,57	0	
6	STANDARD	164,44	12	LZ_BK8	39,85	0	
7	STANDARD	-58,08	2,5	LZ_F1	40,97	0	
8	STANDARD	58,08	10	LZ_K8	42,84	0	
9	STANDARD	-169,04	32,91		43,94	0	
IMA	STANDARD	Infinity			52,08	0	

CARDINAL POINTS:

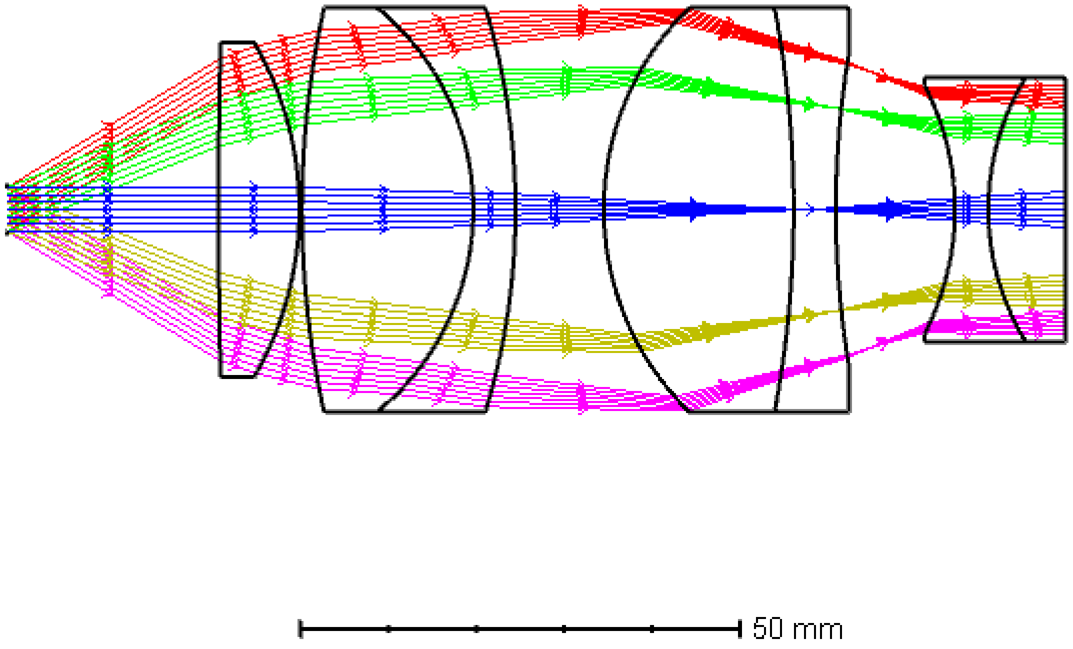
Object space positions are measured with respect to surface 2.
Image space positions are measured with respect to surface 9.
The index in both the object space and image space is considered.

W = 0,546074 (Primary)

	Object Space	Image Space
Focal Length :	-49,092314	49,092314
Focal Planes :	-41,244366	32,906743
Principal Planes :	7,847947	-16,185571
Anti-Principal Planes :	-90,336680	81,999056
Nodal Planes :	7,847947	-16,185571
Anti-Nodal Planes :	-90,336680	81,999056

10.Eye-piece $f' = 26$, $D = 5$ mm, $2\omega = 62°$

7 lenses, focal length $f' = 25.89$, pupil diameter $D = 5$ mm, full angular field $2\omega = 62°$, pupil position 24 mm with respect to the lens.




```
GENERAL LENS DATA:

Surfaces                   :                    13
Stop                       :                     1
System Aperture            :    Entrance Pupil Diameter =    5
Glass Catalogs             :    LZOS
Effective Focal Length     :              25,86145 (in image space)
Back Focal Length          :             -20,77396
Total Track                :                 120,3
Image Space F/#            :              5,172289
Image Space NA             :            0,09622045
Stop Radius                :                   2,5
Paraxial Image Height      :              15,64171
Entrance Pupil Diameter    :                     5
Field Type                 :    Angle in degrees
Maximum Radial Field       :               31,1667
Primary Wavelength [µm]    :              0,546074

Fields          : 3
Field Type                 :    Angle in degrees
 #        X-Value          Y-Value            Weight
 1           0,000000         0,000000           1,000000
 2           0,000000        22,034857           1,000000
 3           0,000000        31,166700           1,000000

Wavelengths     : 3
Units: µm
 #           Value            Weight
 1           0,479991         1,000000
 2           0,546074         1,000000
 3           0,643847         1,000000
```

SURFACE DATA SUMMARY:

Surf	Type	Radius	Thickness	Glass	Clear Diam	Conic	Comment
OBJ	STANDARD	Infinity	Infinity		0	0	
STO	STANDARD	Infinity	24		5	0	pupil
2	STANDARD	727,8	9,2	LZ_K8	34,28	0	
3	STANDARD	-37,58	0,3		37,16	0	
4	STANDARD	105,93	19,5	LZ_TK16	40,77	0	
5	STANDARD	-29,51	4,8	LZ_TF4	42,06	0	
6	STANDARD	-78,7	10		44,87	0	
7	STANDARD	31,92	21,6	LZ_TK16	45,76	0	
8	STANDARD	-122,46	4,8	LZ_TF2	38,67	0	
9	STANDARD	105,93	13,5		33,74	0	
10	STANDARD	-30,41	3,8	LZ_BK10	28,10	0	
11	STANDARD	28,58	8,8	LZ_TF4	28,64	0	
12	STANDARD	Infinity	-20,76		28,30	0	
IMA	STANDARD	Infinity			30,73	0	

CARDINAL POINTS:

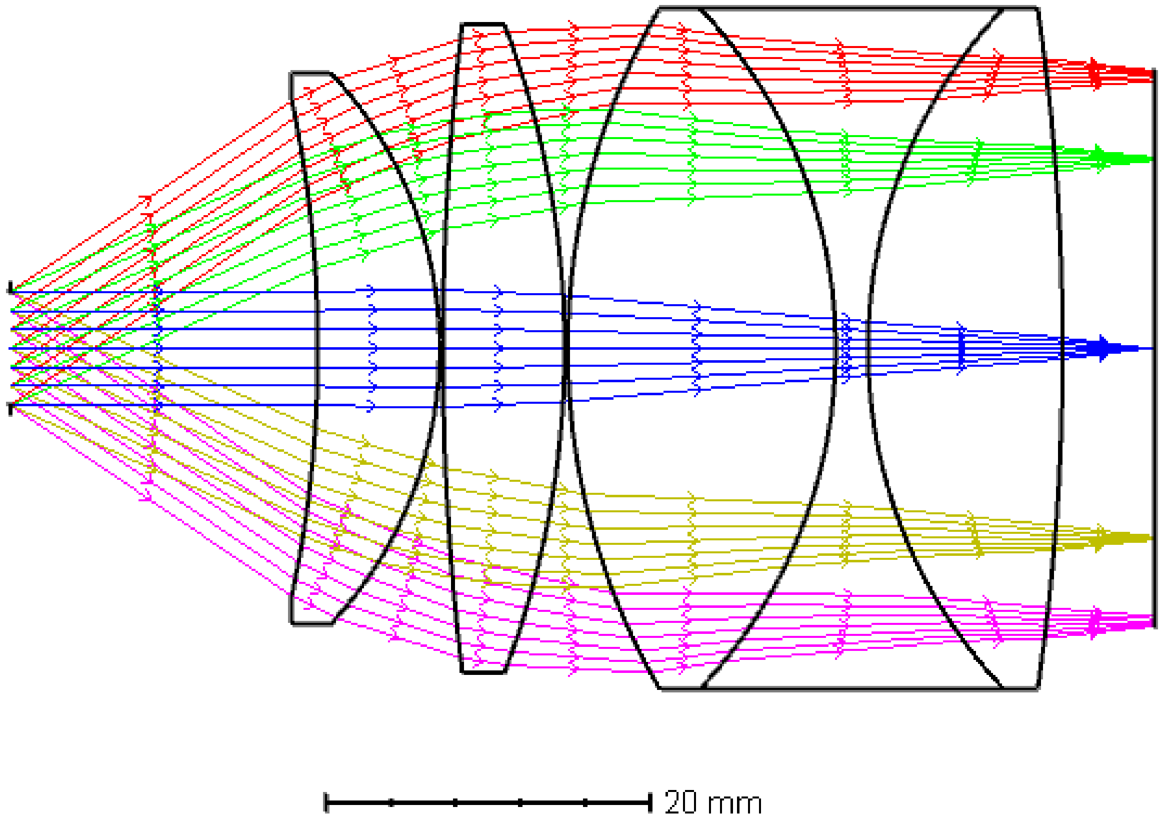
Object space positions are measured with respect to surface 2.
Image space positions are measured with respect to surface 12.
The index in both the object space and image space is considered.

W = 0,546074 (Primary)

	Object Space	Image Space
Focal Length :	-25,861447	25,861447
Focal Planes :	-23,707262	-20,773958
Principal Planes :	2,154185	-46,635404
Anti-Principal Planes :	-49,568709	5,087489
Nodal Planes :	2,154185	-46,635404
Anti-Nodal Planes :	-49,568709	5,087489

11.Eye-piece $f' = 28$, $D = 7$ mm, $2\omega = 68°$

5 lenses, focal length $f' = 27.96$, pupil diameter $D = 7$ mm, full angular field $2\omega = 68.2°$, pupil position 18.95 with respect to the lens.




```
GENERAL LENS DATA:

Surfaces                  :                 10
Stop                      :                  1
System Aperture           :    Entrance Pupil Diameter =    7
Glass Catalogs            :    LZOS
Effective Focal Length    :           27,96788  (in image space)
Back Focal Length         :           5,682718
Image Space F/#           :           3,995412
Image Space NA            :           0,124175
Stop Radius               :                3,5
Paraxial Image Height     :           18,93568
Entrance Pupil Diameter   :                  7
Field Type                :    Angle in degrees
Maximum Radial Field      :               34,1
Primary Wavelength [µm]   :           0,546074

Fields          : 3
Field Type                :    Angle in degrees
 #       X-Value          Y-Value            Weight
 1          0,000000         0,000000          1,000000
 2          0,000000        24,108700          1,000000
 3          0,000000        34,100000          1,000000
```

Wavelengths : 3
Units: µm

#	Value	Weight
1	0,479991	1,000000
2	0,546074	1,000000
3	0,643847	1,000000

SURFACE DATA SUMMARY:

Surf	Type	Radius	Thickness	Glass	Clear Diam	Conic	Comment
OBJ	STANDARD	Infinity	Infinity		0	0	
STO	STANDARD	Infinity	18,95		7	0	pupil
2	STANDARD	-73,11	7,5	LZ_K8	30,48	0	
3	STANDARD	-24,83	0,2		33,20	0	
4	STANDARD	167,49	7,5	LZ_K8	38,18	0	
5	STANDARD	-55,46	0,2		39,12	0	
6	STANDARD	41,69	16,5	LZ_BK8	40,18	0	
7	STANDARD	-30,48	2	LZ_TF1	38,87	0	
8	STANDARD	30,48	12	LZ_K8	36,30	0	
9	STANDARD	-142,56	5,68		35,99	0	
IMA	STANDARD	Infinity			34,41	0	

CARDINAL POINTS:

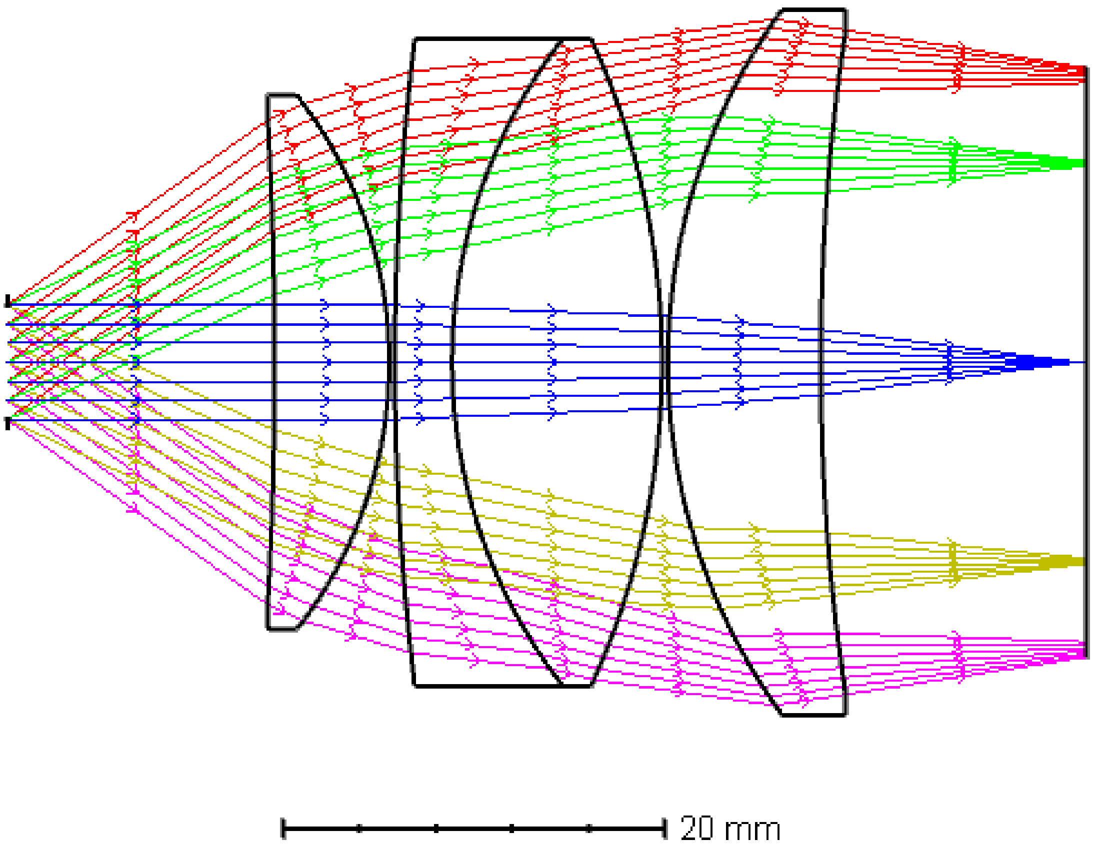
Object space positions are measured with respect to surface 2.
Image space positions are measured with respect to surface 9.
The index in both the object space and image space is considered.

W = 0,546074 (Primary)

	Object Space	Image Space
Focal Length :	-27,967881	27,967881
Focal Planes :	-19,935047	5,682718
Principal Planes :	8,032834	-22,285163
Anti-Principal Planes :	-47,902928	33,650598
Nodal Planes :	8,032834	-22,285163
Anti-Nodal Planes :	-47,902928	33,650598

12.Eye-piece $f' = 24$, $D = 6$ mm, $2\omega = 71°$

4 lenses, focal length $f' = 27.96$, pupil diameter $D = 6$ mm, full angular field $2\omega = 71°$, pupil position 14 mm with respect to the lens.




```
GENERAL LENS DATA:

Surfaces                   :                    9
Stop                       :                    1
System Aperture            :    Entrance Pupil Diameter =    6
Glass Catalogs             :    LZOS
Effective Focal Length     :             23,95814  (in image space)
Back Focal Length          :             13,94937
Image Space F/#            :             3,993023
Image Space NA             :            0,1242481
Stop Radius                :                    3
Paraxial Image Height      :             17,08917
Entrance Pupil Diameter    :                    6
Field Type                 :    Angle in degrees
Maximum Radial Field       :                 35,5
Primary Wavelength [µm]    :             0,546074

Fields            : 3
Field Type                 :    Angle in degrees
 #        X-Value          Y-Value              Weight
 1          0,000000         0,000000             1,000000
 2          0,000000        25,098500             1,000000
 3          0,000000        35,500000             1,000000
```

Wavelengths : 3
Units: µm

#	Value	Weight
1	0,479991	1,000000
2	0,546074	1,000000
3	0,643847	1,000000

SURFACE DATA SUMMARY:

Surf	Type	Radius	Thickness	Glass	Clear Diam	Conic	Comment
OBJ	STANDARD	Infinity	Infinity		0	0	
STO	STANDARD	Infinity	14		6	0	pupil
2	STANDARD	-222,8	6	LZ_K8	25,45	0	
3	STANDARD	-22,7	0,3		27,11	0	
4	STANDARD	139,32	3	LZ_TF4	30,58	0	
5	STANDARD	27,8	11	LZ_BK8	32,37	0	
6	STANDARD	-40,55	0,3		33,45	0	
7	STANDARD	31,62	8	LZ_BK8	36,09	0	
8	STANDARD	115,88	13,95		35	0	
IMA	STANDARD	Infinity			31,04731	0	

CARDINAL POINTS:

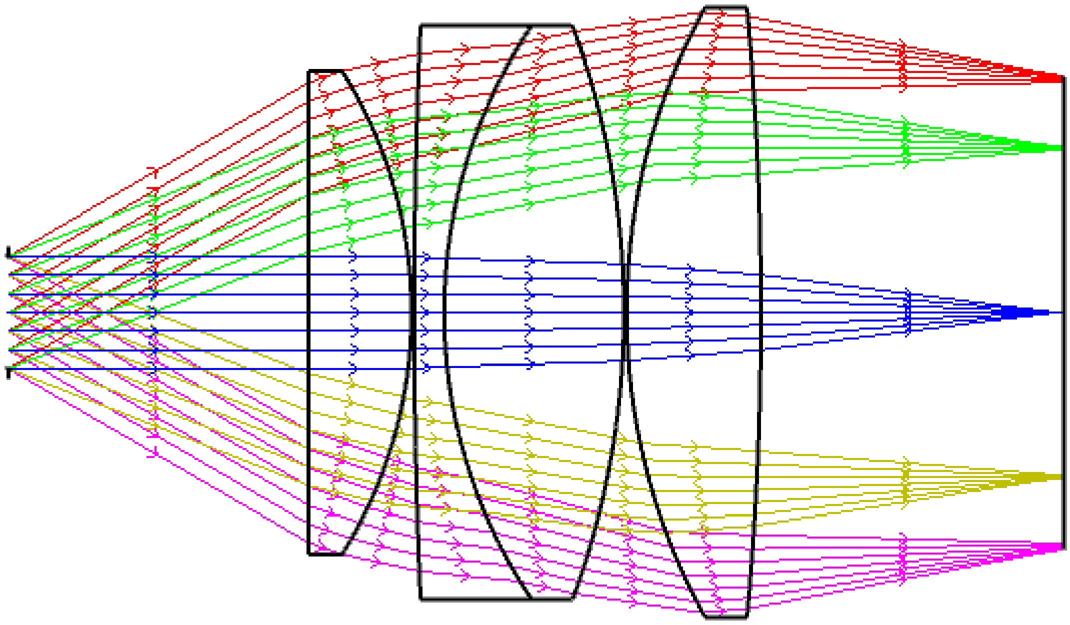
Object space positions are measured with respect to surface 2.
Image space positions are measured with respect to surface 8.
The index in both the object space and image space is considered.

W = 0,546074 (Primary)

	Object Space	Image Space
Focal Length :	-23,958138	23,958138
Focal Planes :	-14,748532	13,949369
Principal Planes :	9,209606	-10,008769
Anti-Principal Planes :	-38,706670	37,907507
Nodal Planes :	9,209606	-10,008769
Anti-Nodal Planes :	-38,706670	37,907507

13.Eye-piece $f' = 25$, $D = 6.25$ mm, $2\omega = 60°$

4 lenses, focal length $f' = 24.95$, pupil diameter $D = 6.25$ mm, full angular field $2\omega = 60°$, pupil position 16.8 mm with respect to the lens.




```
GENERAL LENS DATA:

Surfaces                  :                    9
Stop                      :                    1
System Aperture           :    Entrance Pupil Diameter =    6,25
Glass Catalogs            :    LZOS
Effective Focal Length    :             24,95697  (in image space)
Back Focal Length         :             16,97037
Image Space F/#           :             3,993115
Image Space NA            :            0,1242453
Stop Radius               :                3,125
Paraxial Image Height     :             14,40891
Entrance Pupil Diameter   :                 6,25
Field Type                :    Angle in degrees
Maximum Radial Field      :                   30
Primary Wavelength [µm]   :             0,546074

Fields          : 3
Field Type                :    Angle in degrees
 #        X-Value          Y-Value           Weight
 1        0,000000         0,000000          1,000000
 2        0,000000        21,210000          1,000000
 3        0,000000        30,000000          1,000000


Wavelengths     : 3
Units: µm
 #          Value            Weight
 1          0,479991         1,000000
```

2	0,546074	1,000000
3	0,643847	1,000000

SURFACE DATA SUMMARY:

Surf	Type	Radius	Thickness	Glass	Clear Diam	Conic	Comment
OBJ	STANDARD	Infinity	Infinity		0	0	
STO	STANDARD	Infinity	16,8		6,25	0	pupil
2	STANDARD	Infinity	5,76	LZ_K8	25,65	0	
3	STANDARD	-25,31	0,15		26,96	0	
4	STANDARD	363,41	1,68	LZ_TF3	28,86	0	
5	STANDARD	28,57	10,03	LZ_K8	30,11	0	
6	STANDARD	-45,87	0,15		31,41	0	
7	STANDARD	35,09	7,52	LZ_K8	33,52	0	
8	STANDARD	-185,47	16,97		33,07	0	
IMA	STANDARD	Infinity			26,45	0	

CARDINAL POINTS:

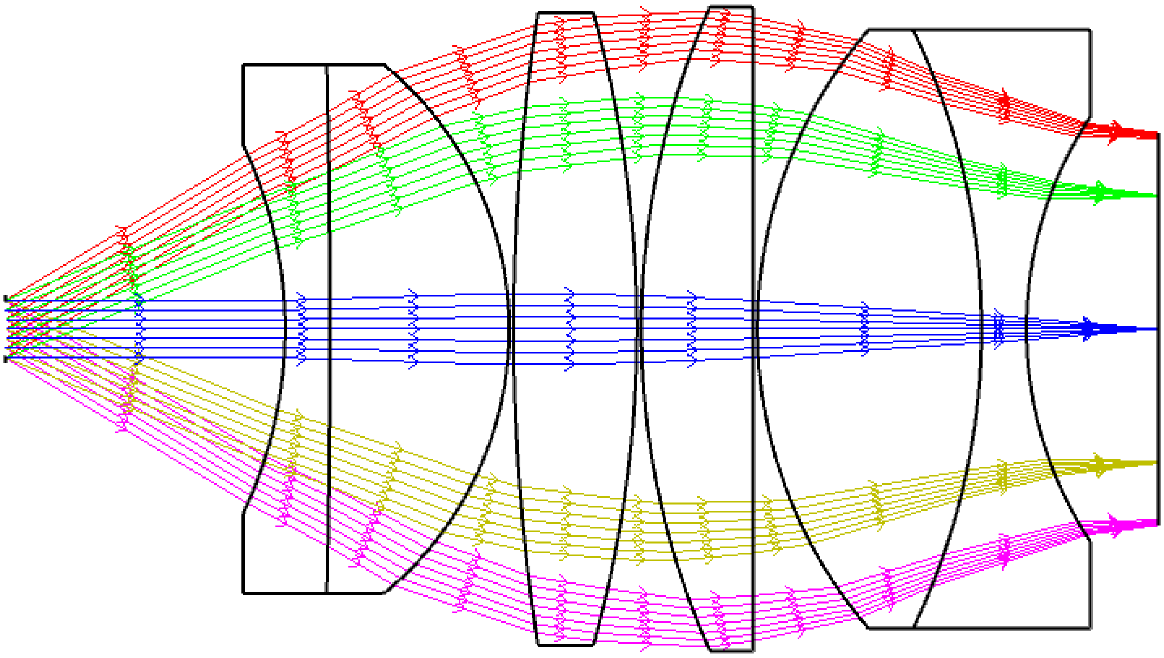
Object space positions are measured with respect to surface 2.
Image space positions are measured with respect to surface 8.
The index in both the object space and image space is considered.

W = 0,546074 (Primary)

	Object Space	Image Space
Focal Length :	-24,956968	24,956968
Focal Planes :	-15,413325	16,970370
Principal Planes :	9,543643	-7,986598
Anti-Principal Planes :	-40,370292	41,927338
Nodal Planes :	9,543643	-7,986598
Anti-Nodal Planes :	-40,370292	41,927338

14.Eye-piece $f' = 30$, $D = 5$ mm, $2\omega = 62°$

6 lenses, focal length $f' = 30.174$, pupil diameter $D = 5$ mm, full angular field $2\omega = 62°$, pupil position 24.3 mm with respect to the lens.




```
GENERAL LENS DATA:

Surfaces                    :                  12
Stop                        :                   1
System Aperture             :    Entrance Pupil Diameter =    5
Glass Catalogs              :    LZOS
Ray Aiming                  :    Off
Effective Focal Length      :            30,17354  (in image space)
Back Focal Length           :            11,47912
Image Space F/#             :            6,034708
Image Space NA              :          0,08257112
Stop Radius                 :                 2,5
Paraxial Image Height       :            18,13009
Entrance Pupil Diameter     :                   5
Field Type                  :    Angle in degrees
Maximum Radial Field        :                  31
Primary Wavelength [µm]     :            0,546074

Fields          : 3
Field Type                  :    Angle in degrees
 #        X-Value           Y-Value              Weight
 1           0,000000          0,000000            1,000000
 2           0,000000         21,917000            1,000000
 3           0,000000         31,000000            1,000000


Wavelengths     : 3
Units: µm
 #           Value             Weight
 1           0,479991          1,000000
```

2	0,546074	1,000000
3	0,643847	1,000000

SURFACE DATA SUMMARY:

Surf	Type	Radius	Thickness	Glass	Clear Diam	Conic	Comment
OBJ	STANDARD	Infinity	Infinity		0	0	
STO	STANDARD	Infinity	24,3		5	0	pupil
2	STANDARD	-36,98	3,9	LZ_TF4	30,30	0	
3	STANDARD	-981,7	15,6	LZ_TK16	37,74	0	
4	STANDARD	-29,65	0,4		44,50	0	
5	STANDARD	180,3	10,7	LZ_TK16	52,80	0	
6	STANDARD	-101,86	0,4		54,19	0	
7	STANDARD	68,55	9,7	LZ_TK16	55,24	0	
8	STANDARD	Infinity	0,4		54,20	0	
9	STANDARD	39,81	19,5	LZ_TK16	50,23	0	
10	STANDARD	-59,7	3,9	LZ_TF4	45,09	0	
11	STANDARD	33,42	11,48		35,90	0	
IMA	STANDARD	Infinity			34,12	0	

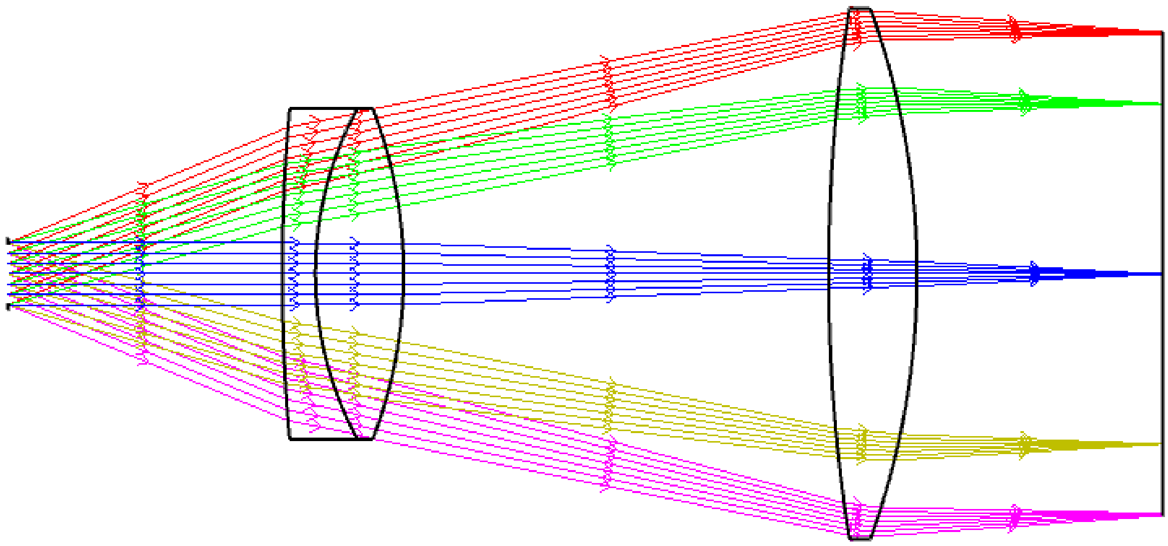
CARDINAL POINTS:

Object space positions are measured with respect to surface 2.
Image space positions are measured with respect to surface 11.
The index in both the object space and image space is considered.
W = 0,546074 (Primary)

	Object Space	Image Space
Focal Length :	-30,173538	30,173538
Focal Planes :	-20,824138	11,479117
Principal Planes :	9,349400	-18,694421
Anti-Principal Planes :	-50,997676	41,652655
Nodal Planes :	9,349400	-18,694421
Anti-Nodal Planes :	-50,997676	41,652655

15.Kellner eye-piece $f' = 56$, $D = 5.6$ mm, $2\omega = 45°$

3 lenses, focal length $f' = 55.92$, pupil diameter $D = 5.6$ mm, full angular field $2\omega = 45°$, pupil position 24.81 mm with respect to the lens.




```
GENERAL LENS DATA:

Surfaces                   :                   7
Stop                       :                   1
System Aperture            :    Entrance Pupil Diameter =    5,6
Glass Catalogs             :    LZOS
Effective Focal Length     :            55,92091  (in image space)
Back Focal Length          :            22,25281
Image Space F/#            :            9,985876
Image Space NA             :          0,05000807
Stop Radius                :                 2,8
Paraxial Image Height      :             23,1632
Entrance Pupil Diameter    :                 5,6
Field Type                 :    Angle in degrees
Maximum Radial Field       :                22,5
Primary Wavelength [µm]    :            0,546074

Fields          : 3
Field Type                 :    Angle in degrees
 #       X-Value          Y-Value          Weight
 1          0,000000         0,000000         1,000000
 2          0,000000        15,907500         1,000000
 3          0,000000        22,500000         1,000000

Wavelengths     : 3
Units: µm
 #          Value            Weight
 1          0,479991         1,000000
 2          0,546074         1,000000
 3          0,643847         1,000000
```

SURFACE DATA SUMMARY:

Surf	Type	Radius	Thickness	Glass	Clear Diam	Conic	Comment
OBJ	STANDARD	Infinity	Infinity		0	0	
STO	STANDARD	Infinity	24,81		5,6	0	pupil
2	STANDARD	167,49	3	LZ_TF1	26,59	0	
3	STANDARD	31,33	8	LZ_BK6	29,05	0	
4	STANDARD	-41,49	38,5		29,92	0	
5	STANDARD	154,17	8	LZ_K8	47,32	0	
6	STANDARD	-70,47	22,25		47,63	0	
IMA	STANDARD	Infinity			43,90	0	

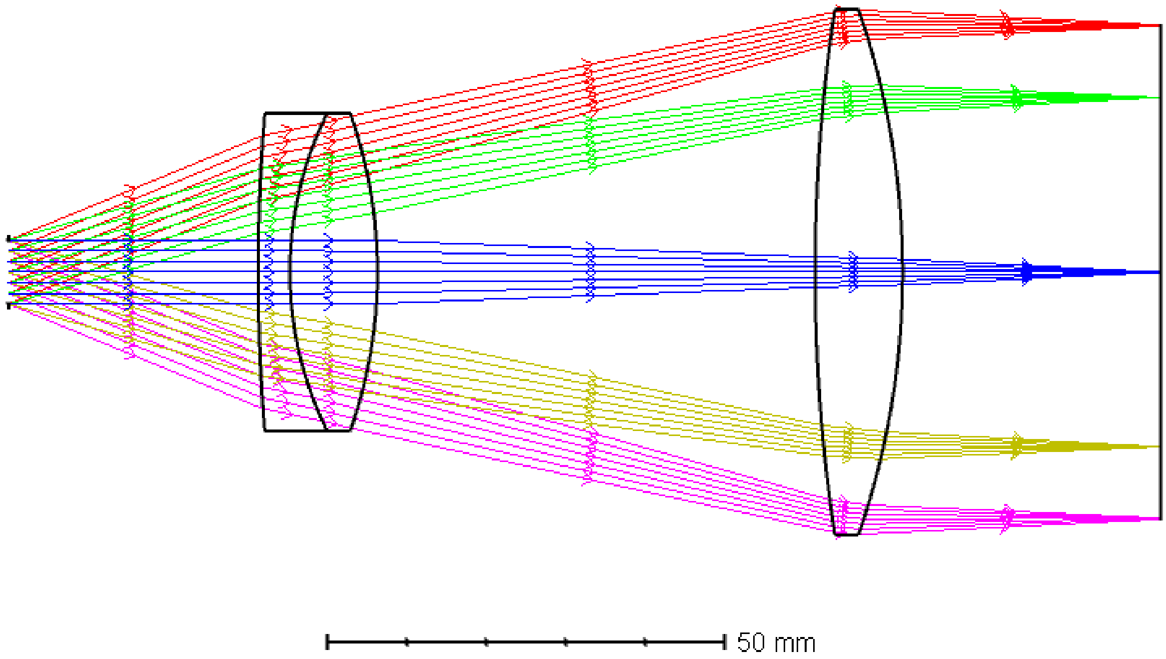
CARDINAL POINTS:

Object space positions are measured with respect to surface 2.
Image space positions are measured with respect to surface 6.
The index in both the object space and image space is considered.
W = 0,546074 (Primary)

	Object Space	Image Space
Focal Length :	-55,920908	55,920908
Focal Planes :	-24,146712	22,252814
Principal Planes :	31,774196	-33,668094
Anti-Principal Planes :	-80,067620	78,173722
Nodal Planes :	31,774196	-33,668094
Anti-Nodal Planes :	-80,067620	78,173722

16.Kellner eye-piece $f' = 80$, $D = 8$ mm, $2\omega = 45°$

3 lenses, focal length $f' = 80.034$, pupil diameter $D = 8$ mm, full angular field $2\omega = 44.7°$, pupil position 31.37 mm with respect to the lens.




```
GENERAL LENS DATA:

Surfaces                    :                    7
Stop                        :                    1
System Aperture             :    Entrance Pupil Diameter =    8
Glass Catalogs              :    LZOS
Ray Aiming                  :    Off
Effective Focal Length      :             80,03368  (in image space)
Back Focal Length           :             32,43617
Image Space F/#             :             10,00421
Image Space NA              :           0,04991666
Stop Radius                 :                    4
Paraxial Image Height       :             32,90582
Entrance Pupil Diameter     :                    8
Field Type                  :    Angle in degrees
Maximum Radial Field        :                22,35
Primary Wavelength [µm]     :             0,546074

Fields            : 3
Field Type                  :    Angle in degrees
 #       X-Value          Y-Value           Weight
 1          0,000000         0,000000          1,000000
 2          0,000000        15,801450          1,000000
 3          0,000000        22,350000          1,000000


Wavelengths       : 3
Units: µm
 #          Value            Weight
 1          0,479991          1,000000
 2          0,546074          1,000000
```

3 0,643847 1,000000

SURFACE DATA SUMMARY:

Surf	Type	Radius	Thickness	Glass	Clear Diam	Conic	Comment
OBJ	STANDARD	Infinity	Infinity		0	0	
STO	STANDARD	Infinity	31,37		8	0	pupil
2	STANDARD	239,9	4	LZ_TF1	34,30	0	
3	STANDARD	44,87	11	LZ_BK6	37,37	0	
4	STANDARD	-59,7	55		39,25	0	
5	STANDARD	220,8	11	LZ_K8	65,29	0	
6	STANDARD	-100,93	32,44		65,82	0	
IMA	STANDARD	Infinity			62,26	0	

CARDINAL POINTS:

Object space positions are measured with respect to surface 2.
Image space positions are measured with respect to surface 6.
The index in both the object space and image space is considered.

W = 0,546074 (Primary)

	Object Space	Image Space
Focal Length :	-80,033678	80,033678
Focal Planes :	-35,209409	32,436173
Principal Planes :	44,824269	-47,597504
Anti-Principal Planes :	-115,243087	112,469851
Nodal Planes :	44,824269	-47,597504
Anti-Nodal Planes :	-115,243087	112,469851

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Optical systems design: course project guide

Original version
Editorial-Publishing Department of ITMO University
EP Department Head N. Gusarova
Signed to print
Order No
Printed circulation
Risograph printing

Editorial-Publishing Department of
ITMO University
197101, Saint Petersburg, Kronverkskiy pr., 49