Afocal Mirror Systems with Small Axial Dimensions

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Abstract

The searching and designing new solutions for mirror systems, including afocal ones, has been studied for decades. In the design, it has always been difficult to combine optimization and cost. Nowadays, the problem remains relevant. The widespread use of mirror systems is due to some aspects: thermal stability, high resolution in a wide spectral range, and the absence of image defects due to chromatic aberrations. All this provides superior performance compared to lens systems. The purpose of this paper is the design of two compact afocal mirror systems with small axial dimensions.

Schemes of afocal three mirror systems with small axial dimensions are presented. The schemes can also be called compacts. A study was made of systems in which the diameter of the aperture diaphragm in the primary mirror is modified, which leads to a more compact system.

A calculation algorithm of new the systems is proposed, with correction of the image curvature. A summary of formulas of the main parameters of the system is given, and various design solutions are calculated for angular field of view $2\omega = 20'$ and diameter of the entrance pupil $D = 35$ and $D = 70$ mm.

Computer simulations were performed in the *Opal*, *Zemax*, and *Code V* software. The designed systems have good correction of aberrations for the given characteristics: in the spot diagrams, the values of the RMS scatter spot do not exceed 1,35 µm; GEO radius (distance from the reference point) – 0.105 µm; together with Airy disk sizes of about 9.16 µm, indicating that the images are close to diffraction.

The calculated systems can be successfully applied as part of a more complex system, as well as in systems with a synthesized aperture.

Keywords: mirror systems, afocal systems, compact systems, calculation optics, image quality.

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Афокальные зеркальные системы с малыми осевыми габаритами

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В настоящие время проблема поиска и проектирования новых схемных решений зеркальных систем, включая афокальные, остается актуальной. Широкое применение зеркальных систем в астрономии, спектральных приборах, лазерном оборудовании и других приложениях обусловлено некоторыми их достоинствами: высоким разрешением в широком спектральном диапазоне, отсутствием дефектов изображения, возникающих из-за хроматических аберраций и ограничений по апертуре, связанных с размерами заготовок, выигрыш по весу. Целью данной работы являлось создание компактных афокальных зеркальных систем с малыми осевыми габаритами.

Представлены схемы конструкций афокальных зеркальных систем из трех параболических зеркал с малыми осевыми габаритами. Проведено исследование афокальных систем, в которых относительное отверстие первичного зеркала, определяющее диаметр апертурной диафрагмы, оптимизировано с целью создания более компактной системы.

Предложен алгоритм параметрического расчета новых композиций с коррекцией кривизны изображения. Дана сводка формул основных конструктивных параметров системы, и рассчитаны различные варианты конструктивного решения для углового поля зрения $2\omega = 20'$, диаметров входного зрачка $D = 35$ мм и $D = 70$ мм.

Проведено численное моделирование в программных средах *Opal*, *Zemax* и *Code V*. Разработанные системы имеют хорошие коррекционные возможности для заданных оптических характеристик: в диаграммах волнового фронта значения величин радиального размера пятна рассеяния не превышают 1,35 мкм; радиус *GEO* (величина расстояния от опорной точки) – 0,105 мкм; вместе со значениями размера диска Эйри около 9,16 мкм, карта волнового фронта на плоскости изображения показывает информацию о среднеквадратичной ошибке. Все это указывает на то, что изображения близки к дифракционным.

Рассчитанные системы могут быть успешно применены в составных зеркальных системах в качестве насадок к регистрирующим объективам, работающим в различных областях спектра (особенно в ИК диапазоне), а также в системах с синтезированной апертурой.

Ключевые слова: зеркальные системы, афокальные системы, компактные системы, расчёт оптических схем, качество изображения.

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Introduction

The searching and designing new solutions for mirror systems, including afocal ones, has been studied for decades. In the design, it has always been difficult to combine optimization and cost. Nowadays, the problem remains relevant. The widespread use of mirror systems [1] (in astronomy, spectral instruments, laser equipment, and other applications) is due to some aspects of mirror systems: thermal stability, high resolution in a wide spectral range, and the absence of image defects due to chromatic aberrations. All this provides superior performance compared to lens systems.

To this day, some ways to solve the problem of optimizing mirror telescopic systems continue to improve. One of the ways used for optimization is the study of compact mirror systems [2]. In general, device compacting is becoming an increasingly frequent requirement for many applications, both in imaging and non-imaging optics [3]. "Compacting" in this case means a reduction in the amount of space between the inlet and the outlet without reducing the optical characteristics. The advantages of compact systems include: small axial length, weight reduction, increased portability of devices, profitability of materials.

In addition, the increase in the path traveled by light, which is created in a compact system, in some cases, is one of the most effective ways to increase the sensitivity of devices, which is interesting for such fields of technology as spectroscopy [4]. Recently, to solve special problems, compositions of telescopic mirror systems have been found, that have the potential to become much more compact.

In this new field of research, afocal systems, also called telescopes, can be widely used in designing schemes. This is because afocal systems are used, not only independently (together with the eye of the observer), but also as part of a more complex system (as an adapter piece), which is beneficial for creating their modules in more compact versions. In many cases, laser optics requires the use of optical systems that operate between endless configurations. Such systems, commonly called beam expanders, are actually telescopes. They are used to control the energy of laser beams, correct beam divergence, study beam propagation, and also to reduce the field of view and expand the magnification in *FLIR* systems [5]. In geodetic instruments for photo-registration systems of distant objects, mirror-lens afocal devices are often successfully used [6].

The purpose of this paper is the design of compact afocal mirror systems with multiple reflections from the primary mirror, where the quart-parabolic Mersenne systems of three mirrors serve as the basic modules of these compositions.

Analysis of compaction methods

In the literature [7–9], we can found several methods to achieve a best compactness of optical systems. In [7], a two-mirror compact system is presented, where the primary mirror has a spherical shape, and a secondary mirror is placed in its paraxial focus, while the distance between the mirrors is equal to half the radius of the primary; spherical aberration is completely eliminated. Note that compactness in such work owes its name to a specific arrangement of its mirrors due to its displacement, which changes the length of the system.

Also, [8] presents a new compact optical system, which can be described as a modified Gregory system. The compact telescope is created from a standard Gregorian system by flipping the secondary mirror over a folding mirror installed approximately in the middle of the optical path between primary and secondary mirrors. In this manner, the primary mirror is constructed with concentric "double curved" geometry, and a central obscuring folding mirror which matches the diameter of the smaller curve of the primary is mounted a short distance in front. This "double curved" geometry is easily produced using diamond turning technology, and the result is a compact telescope approximately 1/2 the length of a regular Gregorian telescope and roughly 2/3 the length of a Cassegrain telescope.

In [9], it is noted, that one of the ways to achieve compactness is by dividing a systems into multiple channels with smaller apertures. This allows you to increase the field of view using the same focal length. This allows for bigger field of view using the same focal length. It can also be effective in improving the system performance, since each channel can be designed separately. This method is based on multichannel optical systems that exist in nature. They are known as insect eyes. Each eye consists of a large number of small visual systems called ommatidia. Based on these studies, they offer new solutions for compact multi-channel optical systems for use in imaging and non-imaging optics.

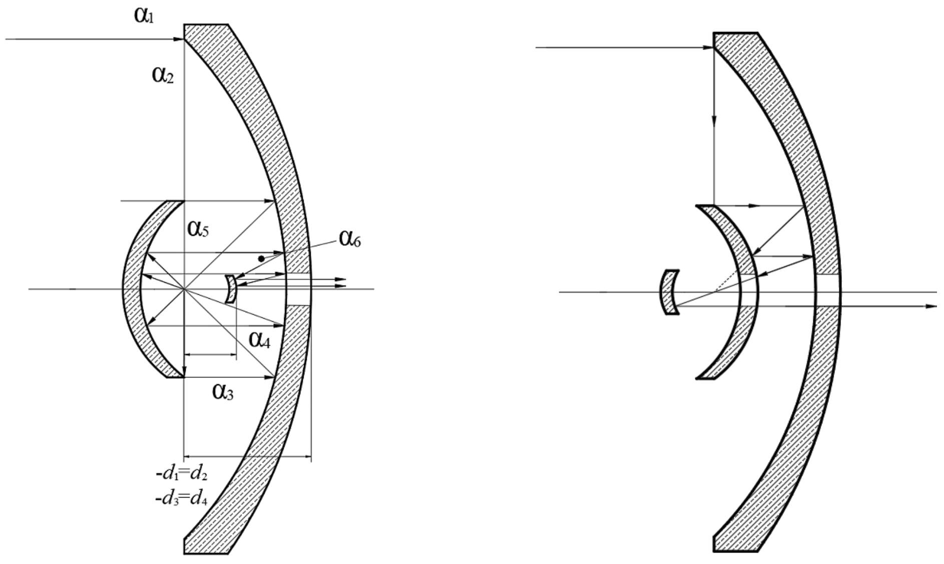
Description and calculation of afocal mirror systems with small axial dimensions

The object of this study is the compact design of afocal mirror systems with multiple reflections from the primary mirror, shown in Figure 1. The basic modules of these compositions are the quarter-parabolic Mersenne systems of three mirrors.

These afocal systems allow the possibility of eliminating spherical aberration, coma, astigmatism and even image curvature.

In such a scheme of three mirrors, two constructive solutions are possible – when the first of the Mersenne systems is a keplerian type system, and when the first of the systems is a galilean type system.

In Figure 1*a* keplerian type diagram is presented. The first and third mirrors have equal radii of curvature of the surfaces.



a *b*

Figure 1 – Afocal mirror systems with small axial dimensions: *a* – keplerian type system; *b* – galilean type system

Graphic calculation of the primary parabolic mirror

One of the optimized parameters of the mirror telescopic system is their overall dimensions.

In these schemes, the compacting system is guaranteed by the pronounced shape of the primary mirror and a certain relationship of diameter and axial dimensions, the mirror has a high relative aperture.

To evaluate the values of the longitudinal dimensions, it is advisable to establish the compaction coefficient equal to the relationship between the axial length of the system L and the diameter of the first mirror D_1:

$$K_l = \frac{L}{D_1}, \qquad (1)$$

where L is the length of the system; D_1 is the diameter of the first mirror (entrance pupil).

The geometric shape of the meridional curve of the primary mirror is determined by a parabola, the property of which is equivalent to the analytical definition of the given equation, the first coefficient of which is determined by the vertex radius of the surface:

$$y^2 = 2r_1x.$$

Diameter of the primary mirror (Figure 2):

$$D = 2r_1.$$

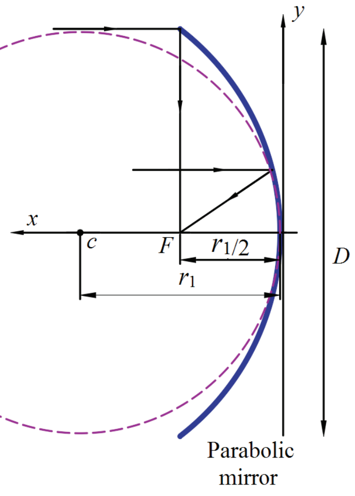


Figure 2 – Graphic calculation of the primary parabolic mirror of the afocal system

We have a coordinate relationship:

$$x = \frac{r_1}{2} f' = r_1 / 2, \qquad (2)$$

$$y^2 = r_1^{\,2} D/f' = 4.$$

Determine the relative aperture of the primary mirror:

$$y = r_1 D/f' = 1{:}0.25,$$

where r_1 – is the radius of the primary parabolic mirror of Kepler type systems; f' – is the distance from the top of the mirror to the focus F; D – is the diameter of the mirror.

Algorithm calculation

The surface of the mirrors (Figure 1) shows the course of the first ray with parameters α_S and h_S going through the system (S is the surface number).

We compose the calculation algorithm. When calculating, we use standard notation, taking into account the rule of signs:

angles α_S and heights h_S of the first ray,
refractive indices n_S, in front of the S-th surface,
axial distances d_S.

We define the normalization conditions and calculate the necessary parametric characteristics for a given value of visible magnification Γ.

Moreover, we have $n_1 = n_3 = n_5 = n_7$ и $n_2 = n_4 = n_6 = -1$.

1. The angles and heights of the first ray for a given visible magnification Γ:

$$\alpha_1 = \alpha_3 = \alpha_5 = \alpha_7 = 0;\ h_1 = 1;$$

$$\alpha_2 = \frac{h_1}{f_1'} = -1;\ h_4 = h_3 - \alpha_4 d_3;$$

$$h_2 = h_3;\ \alpha_4 = \frac{h_3}{f_1'} = -h_3 = -h_2; \qquad (3)$$

$$h_4 = h_5;\ \alpha_6 = \frac{h_4}{f_1'} = -h_4;$$

$$h_6 = \frac{1}{\Gamma};\ h_6 = h_5 - \alpha_6 d_5.$$

2. Axial distances:

$$d_1 = 1 - h_2;\ d_3 = \frac{h_4 - h_2}{-\alpha_4};\ d_5 = \frac{1}{\Gamma h_4} - 1. \qquad (4)$$

3. The curvature radii of the surfaces:

$$r_1 = \frac{2}{\alpha_2} = -2;\ r_2 = \frac{2h_2}{\alpha_2} = -2h_2;\ r_3 = \frac{2h_2}{\alpha_4} = -2;$$

$$r_4 = \frac{2h_4}{\alpha_4};\ r_5 = -2;\ r_6 = \frac{2}{h_4 \Gamma}. \qquad (5)$$

The algorithm for calculating the compact afocal mirror system of the galilean type, shown in Figure 1*b*, is compiled similarly.

Modeling and discussion of results

We calculate α_4, for a given visible magnification Γ. Substituting α_4, we determine the height h_4 and obtain parametric characteristics in relative values.

$$r_1 = -2;\ r_2 = 0.86;\ r_3 = -2;$$

$$r_4 = 0.86;\ r_5 = -2;\ r_6 = \frac{2}{0.186}; \qquad (6)$$

$$-d_1 = d_2 = -d_3 = d_4 = 1{,}43;\ d_5 = \frac{1}{0.186} - 1.$$

Next, we carry out an anastigmatic correction in the field of aberrations of the 3rd order. As a result, deformations of mirror surfaces σ_S are obtained. They are defined by the squared eccentricity of the second-order meridional curves of the mirror surfaces. For parabolic shape of mirrors:

$$\sigma_1 = \sigma_2 = \sigma_3 = \sigma_4 = \sigma_5 = \sigma_6 = -1. \qquad (7)$$

The compact afocal systems of the kepler and galilean type were calculated according to formulas (5) for the following real values: $N = 0.25$; angular field of view $2\omega = 20''$, entrance pupil diameter $D = 35$ mm and 70 mm, respectively. Design data of the calculated systems of type I and II for the values of the visible magnification $\Gamma = -47^x$ and $\Gamma = 27^x$ are given in Table 1.

Table 1

Results for a visible magnifications $\Gamma = -47^x$ and $\Gamma = 27^x$ (dimensions in mm)

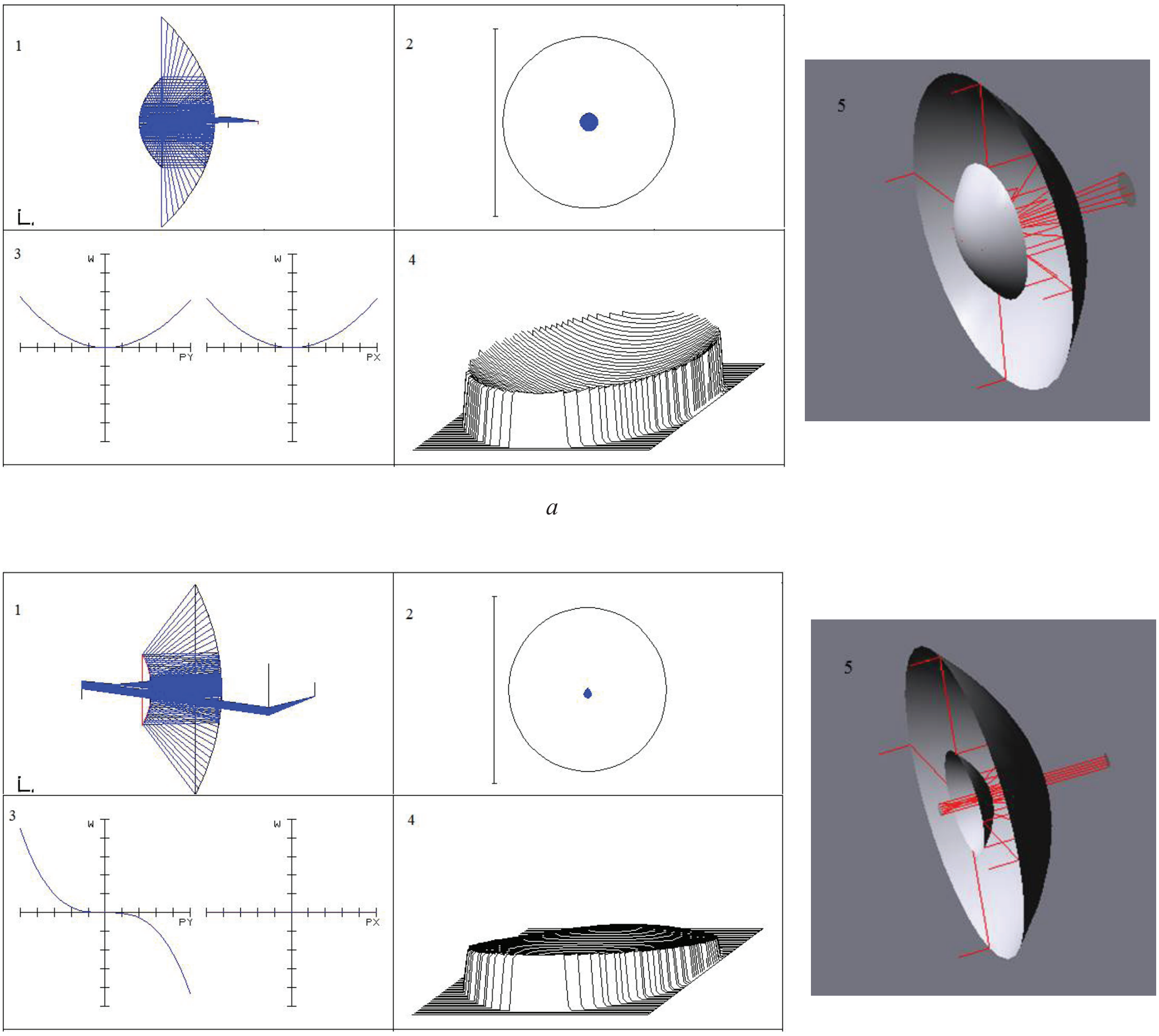
Type of scheme	Γ	r_1	r_2	r_3	r_4	r_5	r_6	d_1	d_2	d_3	d_4	d_5
Kepler type	-47^x	-35	15	-35	15	-35	-4	-25	25	-25	25	15
Galilean type	-27^x	-90	-30	-90	-30	-90	30	-30	30	-30	30	-60

Computer modeling was carried out in software environments for the construction of afocal systems. The aberrations obtained in the software *Opal* are given in Table 2 (Z'_m–Z'_s – astigmatism; Z'_m, Z'_s – meridional and sagittal curvature of the image $\Delta Y'$ % – relative distortion). The results of computer simulation performed in *Zemax* and *Code V* are presented in Figure 3.

Table 2

Aberrational characteristics (calculation in the Opal software)

	$\Delta Y'$ %	Z'_m - Z'_s	Z'_m	Z'_s
$\Gamma = -47^x$	Kepler type			
	1.0926	0.001	1.3105	1.3095
$\Gamma = 27^x$	Galilean type			
	0.1542	0.0024	0.0024	0.0000



a

b

Figure 3 – Computer simulation of compact designs of afocal mirror systems: *a* – kepler-type system; *b* – galilean type system. 1 – computer schemes; 2 – spot diagrams; 3 – transverse aberration graphs; 4 – wavefront maps (calculation in the software zemax); 5 – computer schemes (calculation in the software Code V)

The system has good correction capabilities for specified optical characteristics: in the spot diagrams, the values of the radial size of the RMS scatter spot do not exceed 1.35 µm; GEO radius (distance from the reference point) – 0.105 µm; together with Airy disk sizes of about 9.16 µm, indicating that the images are close to diffraction. A wavefront map on the image plane shows aberration correction information. In this case, the wavefront error RMS is in the order of 0.012 waves. This indicates that wave aberrations (OPDs) are small for arrays passing through the center of the aperture. The systems can be used as part of a more complex system operating in various fields of the spectrum. In addition, they can be used in optical systems with a synthesized aperture [10], and when misaligning the studied afocal systems, telephoto objective with high image quality can be obtained.

Conclusion

A technique is given for calculating compact afocal schemes in which the first and third mirrors have equal radius of curvature of the surfaces. The compacting of the schemes is ensured by the primary mirror having a high relative aperture.

An algorithm for parametric calculation is proposed. Modified normalization conditions are introduced into the calculation algorithm. The calculation was performed for the angular field of view $2\omega = 20'$, the diameter of the entrance pupil $D = 35$ and 70 mm.

Computer simulation was performed in the *Opal*, *Zemax* and *Code V* software environments. It was established, that the system has good aberration correction for specified optical characteristics.

The systems can be used as part of a more complex system operating in various fields of the spectrum. In addition, they can be used in optical systems with a synthesized aperture, and when misaligning the studied afocal systems, telephoto objective with high image quality can be obtained.

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