All-spherical catadioptric telescope design for wide-field imaging

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The current trend in building medium-size telescopes for wide-field imaging is to use a Ritchey–Chrétien (RC) design with a multilens corrector near the focus. Our goal is to find a cost-effective alternative design to the RC system for seeing-limited observations. We present an \( f/4.5 \) all-spherical catadioptric system with a 1.5° field of view. The system consists of a 0.8 m spherical primary and 0.4 m flat secondary mirror combined with a meniscus lens and followed by a three-lens field corrector. The optical performance is comparable to an equivalent \( f/4.5 \) RC system. We conclude that, for telescopes with apertures up to 2 m, the catadioptric design is a good alternative to the RC system. © 2010 Optical Society of America

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1. Introduction
The classical Ritchey–Chrétien (RC) system employs two hyperboloidal mirrors providing full correction of spherical aberration and coma. Because of aplanatic correction and two-mirror simplicity, the RC design has been an attractive solution for many observatories. However, the RC focal surface is curved—mimicking the shape of the secondary mirror—and astigmatism limits the field of view. These drawbacks become critical for imaging over fields wider than 15–20 arcmin.

Telescopes dedicated for wide-field imaging, such as sky survey systems, usually require fields extending over a few degrees. In addition, field curvature must be corrected to match the flat surface of modern detectors. Both conditions can be fulfilled in the RC system by introducing a multilens corrector near the Cassegrain focus [1–4]. In most designs described in the literature, the field corrector is not part of the original telescope design and is added to the telescope system for a wider field. In contrast to this \textit{ad hoc} strategy, the lens corrector can be incorporated into telescope design from the very beginning. An example of an RC telescope with a three-lens field corrector designed this way is presented and compared to an all-spherical catadioptric system in Section 3.

2. Historical Overview of Popov and Klevtsov Telescope Systems
In spite of diffraction-limited image quality achievable within a 1°–2° field, a major concern is the high cost of manufacturing and testing large aspheric mirrors. In light of this, there have been various attempts at using a spherical primary mirror to achieve a cost-effective solution for astronomical telescopes with catadioptric \([5,6]\) and catoptric correctors \([7–10]\). Two examples of such systems are shown in Figs. 1(a) and 1(b). They are based on the two configurations inspired by Klevtsov [Fig. 1(a)] and Popov [Fig. 1(b)] telescope systems. Both systems use a 0.8 m spherical primary mirror M1 and a three-lens field corrector, which provides a typical \( f \) number for Cassegrain telescopes of \( f/9.5 \). For such an \( f \) number, the secondary group has a noticeable optical power; hence, it is easy to show the advantage of using a Mangin mirror in the Klevtsov system. The secondary group consists of a secondary mirror M2 and a meniscus lens MC. The first design shown in Fig. 1(a), features a Mangin mirror M2 as origin-
ally proposed by Klevtsov [11], while the other system uses a convex spherical secondary M2; see Fig. 1(b). The latter configuration has been proposed by Popov [12]. In its original form, the Popov system [13] did not feature any field corrector and was primarily designed to achieve aplanatic correction by optimizing the curvature and central thickness of the meniscus. The longitudinal chromatic aberration could be corrected by modifying the secondary into a Mangin mirror. As a result, we get a “quasi RC”, the Klevtsov system [11], which is not so well known outside Russia. Klevtsov and Popov systems have some residual field curvature and astigmatism, limiting the field of view to 15–20 arcmin. For a wider field,
one needs a field corrector that is capable of removing astigmatism and flattening the field.

For both design examples presented here, the field corrector is a three-lens system optimized as an integral part of the telescope and not as an *ad hoc* focal reducer [14]. The field corrector is mainly required to keep astigmatism, field curvature, and lateral color to a minimum. The secondary group corrects most spherical aberration and a large fraction of field curvature of the primary mirror. Coma correction is shared between the field corrector and the secondary group, as can be seen from the diagrams in Fig. 2. Aberration balancing enables us to obtain near diffraction-limited image quality within a 1° field at visible wavelengths from 486 to 656 nm.

The system with a Mangin mirror provides better correction of astigmatism and field curvature, which leads to superior image quality; see Figs. 2(a) and 2(b). This is simply because the Mangin mirror offers additional degrees of freedom (compared to the single reflective surface), namely, the glass thickness and shape factor that allow us to adjust intrinsic coma and field curvature. The Mangin mirror is commonly used as a powerful element in catadioptric designs [15, 16].

The flat-field condition can be met by a particular geometry of the three-lens corrector for which its intrinsic field curvature is nearly zero. This is because the secondary group compensates for most field curvature of the primary. The Mangin mirror reduces the overall field curvature in the telescope, while the field corrector eliminates lateral color of the Mangin mirror; see Fig. 2.

In the design featuring only the secondary mirror and meniscus lens, fine-tuning of coma and field curvature is much more difficult. This rules out the flat-field solution, since the field corrector is not capable of removing field curvature and coma without the Mangin mirror. However, by leaving some small amount of residual astigmatism (under-correcting astigmatism of the primary mirror), one can flatten the focal surface [17]. As a result, we achieve near diffraction-limited image quality within a 1° field, as shown in Fig. 3(b). The choice of a 0.8 m aperture is consistent with the pixel size available (8–10 μm) that gives an optimal sampling (2 pixels per width of the point-spread function containing 80% of encircled energy). Aberration balancing is discussed in detail in Section 4.

3. All-Spherical Catadioptric Design Versus Ritchey–Chrétien System

Rapid advances in manufacturing large-size megapixel detectors make it possible to image wider areas of the sky without compromising the telescope angular resolution. For sky survey systems with the field of view over several degrees, one has to use telescopes with a relatively fast focal ratio to keep the detector size within reasonable limits (up to 100 mm). For a 0.8 m telescope to fit a 1.5° field onto a 100 mm × 100 mm detector, one needs to use a focal ratio not greater than 4.5. This is an important requirement that dictates our choice for the optical system configurations considered here.

Figure 4(a) shows an example of a modified RC telescope with a hyperboloidal primary mirror and a planoid aspheric secondary mirror. The necessity to operate at f/4.5 speed with reasonable central obscuration leads to the RC system configuration in which the secondary mirror has no optical power. A dedicated three-lens field corrector eliminates all
residual aberrations of the two-mirror system, in particular astigmatism and field curvature.

The field corrector has significant intrinsic field curvature, which is matched to the field curvature of the primary mirror. By contrast, the field correctors for \( f/9.5 \) catadioptric systems considered in the introductory section have very little intrinsic field curvature. A more detailed coverage of aberration balancing by the three-lens field corrector is given in Section 4.

Figure 4(b) shows an \( f/4.5 \) all-spherical catadioptric design with a flat secondary mirror and an afocal meniscus lens followed by a three-lens field corrector. We also present an unfolded optical layout of the system in Fig. 5 to emphasize the afocal nature of the meniscus and point out the main source of filed curvature (the primary mirror). Note that MC* stands for the second path through the meniscus corrector. Similar to the RC system, the secondary group has no optical power, which is a necessary condition for achieving \( f/4.5 \) speed with tolerable central obscuration and an accessible focal plane position.

The lack of optical power negates the benefit of using a Mangin mirror in the secondary group because, without optical power, the Mangin mirror is unable to reduce coma and field curvature of the primary mirror [15]. However, despite a fewer degrees of freedom in the secondary group, an afocal meniscus is still the key element for compensating spherical aberration of the primary mirror and the three-lens corrector. The latter is responsible for removing overall coma, astigmatism, and field curvature, as well as reducing axial and lateral color of the meniscus lens; see Fig. 6(b).

Figure 7 depicts the spot diagrams for both designs. The modified RC system gives diffraction-limited image quality, while the all-spherical catadioptric system shows a tiny amount of lateral color and coma. In view of the wide field (1.5°) and simplicity of the secondary group (no Mangin mirror), we believe that the presented all-spherical catadioptric design is an attractive alternative to the RC system. The catadioptric design provides a cost-effective solution for sky survey telescopes that do not operate at their diffraction limit due to atmospheric seeing [18] or atmospheric dispersion [19].

The targeted group here is medium-size telescopes with apertures up to 1–2 m, which typically operate without adaptive optics (AO), unless particular attention is given to AO integration into telescope design [20–23]. Thus, the image quality of a typical medium-size telescope is limited by atmospheric seeing. The atmospheric turbulence reduces the sharpness of the image of a point source and blurs the image to the size of the seeing disk. For good seeing conditions, the radius of the seeing disk is about 0.5 arcsec, while the Airy disk radius for an 0.8 m telescope is only 0.15 arcsec.

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Fig. 4. (Color online) \( f/4.5 \) RC system with a planoid secondary and three-lens field corrector(a) and an \( f/4.5 \) all-spherical catadioptric system (b).
4. Balancing Aberrations with Three-Lens Correctors

It is well known that it is possible to correct spherical aberration, coma, and axial color in an air-spaced doublet, as well as in a cemented doublet with a special choice of a glass pair for positive and negative elements [24]. Adding a third lens makes it possible to correct for astigmatism and lateral color if the position of the aperture stop can be adjusted. A good example is a Cooke triplet [25]. In our modified f/4.5 RC telescope design with a three-lens corrector, the position of the aperture stop is given by the primary mirror, and thus the correction of lateral color by the symmetrical placement of lenses with respect to the aperture stop is not feasible [25]. It is necessary to introduce a third glass type in the corrector for lateral color elimination. As we showed in an earlier study, a modified RC system with a doublet field corrector suffers from lateral color [26]. Besides axial and lateral color, we also need to remove four types of monochromatic aberrations. This task is distributed between the two mirrors and the lens corrector.

Adjusting the asphericity of the primary and secondary mirrors, one could always compensate spherical aberration and coma in the field lens corrector. This helps to liberate at least two degrees of freedom in the field corrector for better elimination of other aberrations. In particular, correction of astigmatism and field curvature of the two-mirror system becomes very effective and, as a result, we get well-corrected flat field over nearly two degrees.

As an alternative configuration, one could use a spherical primary mirror followed by a secondary group combining a meniscus lens with a Mangin mirror. This combination also allows us to tune the overall amount of spherical aberration and coma in the telescope. However, in contrast to the modified RC system, the field lens corrector has to compensate a noticeable amount of lateral color originating from the secondary group; see Fig. 2(a). This condition slightly upsets the individual correction of astigmatism and field curvature in the telescope. As a result, these two aberrations have to balance one another,
which is illustrated in Fig. 8 by vertical gray bars representing third- and fifth-order aberration coefficients [27].

It is worth noting that third-order aberration theory alone is not sufficient for finding the optimal configuration of the lens corrector. Using optimization based on real ray tracing together with basic understanding of aberration balancing in the proposed catadioptric systems proves to be more effective.

For a simplified system in which the Mangin mirror is replaced by the flat secondary, the task of coma elimination is passed on to the lens corrector. This puts an additional constraint on the lens corrector and, therefore, leads to even more pronounced residual astigmatism than is necessary to flatten the field; see the black vertical bars in Fig. 8. The choice of glass type for the meniscus lens becomes critical because it helps to reduce the lateral color in the whole system. We have considered N-SF1, N-SF2, F1, and N-BK7 glass for the meniscus lens. The latter is selected as the optimal glass for lateral color correction. The blanks of N-BK7 glass are available in large diameters so, even for a 2 m telescope, manufacturing a 1 m meniscus lens should be feasible.

It is interesting to note that when going from an f/9.5 to f/4.5 system, presented in Figs. 1(b) and 4(b), respectively, the residual lateral color changes its direction as can be seen at the intermediate field points in Figs. 3(b) and 7(b). This indicates that a better choice of glasses might be found.

5. Technical Characteristics of the 0.8 m All-Spherical Catadioptric Telescope

The main optical parameters of for the 0.8 m f/4.5 catadioptric telescope system are given in Table 1. One could see the recommended glasses for the three-lens field corrector used in all systems presented here.

Because the secondary group is the most distant component from the primary mirror, it is important to check the tolerances on its position. Our analysis shows that the tilt of the secondary group within ±1.6 arcmin will reduce the diffraction encircled energy by less than 20%. This is comparable with the
tolerances of the f/4.5 RC system discussed in Section 3.

Figure 9 depicts the diffraction encircled energy for the central, intermediate, and edge point in the field. It is seen that 80% of encircled energy for the point on axis falls within a spot 12 μm in diameter, while the spot at the edge of the field (0.75°) is about 16 μm. The spot size is well matched to the pixel size of 8 μm commonly used for detectors in the visible region. The image scale is 0.057 arcsec/μm (one pixel covers 0.46 arcsec).

The orientation of the meniscus lens is not critical because it has no optical power; however, the suggested lens shape might help to reduce the length of the mounting assembly of the secondary group. The central obscuration due to the secondary group is less than 29% for all field points. The stray light is a notorious problem for astronomical telescopes. Three baffles are needed for our design: extended telescope tube (1.7 m); a flange at the secondary group (0.18 m long and 0.43 m in diameter); and a flange in front of the 3-lens corrector (0.2 m long). In some cases, one could use a folding flat mirror to bring the final focus outside the telescope for minimizing stray light and avoiding the unwanted central opening in the primary mirror [28].

6. Conclusion

In this paper, we propose a simplified all-spherical catadioptric system for a sky survey telescope. Its optical performance is analyzed against a modified RC system. Both designs operate at f/4.5 speed and feature a three-lens field corrector optimized for 1.5° field at the visible wavelengths (from 486 to 656 nm). The basic principles of aberration balancing are discussed in detail. The primary mirror diameter is 0.8 m; however, the proposed system is intended for medium-size telescopes with an aperture up to 1–2 m, which typically operate without adaptive optics, thus being limited by atmospheric seeing. Taking into account the simplicity of the all-spherical catadioptric design and its near diffraction-limited image quality comparable to that of the RC system, we conclude that the catadioptric design provides a cost-effective solution for ground-based sky survey telescopes that do not operate at their diffraction limit due to atmospheric seeing.

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