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Review of design parameters and optical characteristics of the main types of amateur telescopes

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Abstract

This review examines the design principles and image quality performance of the three primary types of amateur astronomical telescopes: refractors, reflectors, and catadioptrics. The study begins with a thorough overview of existing literature, referencing over 150 sources to provide a theoretical introduction for the analysis. Each telescope type is evaluated in terms of its optical construction, aberration control, portability, maintenance, and suitability for both visual observation and astrophotography. Key differences and trade-offs in performance, usability, and cost are discussed. Special attention is given to how each design handles chromatic and spherical aberrations, field curvature, and diffraction effects - factors critical to image sharpness and contrast. The paper concludes with practical recommendations tailored to various user needs, such as planetary observation, deep-sky imaging, or beginner-level stargazing. By synthesizing theoretical insights with practical considerations, this review aims to guide amateur astronomers, educators, and enthusiasts in selecting the most appropriate telescope type for their specific interests and observing goals.

Keywords: astronomical telescope; optical design; refractor; reflector; catadiopter

1. Introduction

Astronomical telescopes have played a crucial role in expanding our understanding of the universe, enabling observations from the visible spectrum to infrared and radio wavelengths. Over the centuries, telescope designs have evolved significantly from early refractors and reflectors to sophisticated space-based observatories equipped with adaptive optics and segmented mirrors. Each design is driven by scientific requirements, such as improved resolution, greater light-gathering power, and minimized optical aberrations.

Astronomers rely on three main types of telescopes: refracting, reflecting, and catadioptric systems. Each design has distinct optical characteristics that influence image quality, such as resolution, contrast, and the correction of various aberrations. This paper examines the fundamental principles behind these telescope types and analyzes their performance in both visual observation and astrophotography. Consideration is given not only to optical performance but also to practical aspects like portability, ease of use, maintenance, and cost. Drawing on a broad range of literature, the paper offers a comparative overview aimed at helping users understand the advantages and limitations of each design. Based on this analysis, recommendations are provided in selecting the most appropriate telescope for specific observational needs.

2. Review of literature

A substantial body of literature exists on the design and development of astronomical telescopes, encompassing both academic publications and practical manuals. Numerous high-quality books are available that explore the theoretical foundations and engineering aspects of telescope construction. These resources can generally be categorized into two distinct groups: those that address the complex requirements and design methodologies of professional observatory-class telescopes, and those that serve as practical guides for amateur telescope makers. While the former often delves into advanced optical theory, precision engineering, and large-scale instrumentation, the latter typically focuses on simplified construction techniques, cost-effective materials, and performance optimization for personal or hobbyist use.

In addition to books, a wide range of peer-reviewed scientific articles contributes to the field by presenting original research, case studies, and technical innovations in telescope optics, mechanical design, and performance analysis. These papers provide valuable insights into recent advancements in optical materials, aberration correction techniques, and adaptive optics systems. The diversity of topics covered in the literature reflects the ongoing evolution of telescope technology and the broad interest it holds for both professional astronomers and dedicated amateurs.

This study incorporates a curated selection of these resources, with over 150 references reviewed to ensure a comprehensive understanding of current trends and foundational concepts in telescope design. The literature survey not only highlights the historical progression of various telescope types but also identifies key contributions that have influenced the design principles of modern amateur telescopes. Through this extensive review, the paper aims to bridge the gap between theoretical knowledge and practical application, providing a solid contextual framework for the comparative analysis that follows.

2.1 Review of books

"The History of the Telescope" by Henry C. King [38] is a comprehensive chronicle detailing the development of the telescope from its invention through the mid-20th century. Originally published in 1955, this work delves into the contributions of renowned figures, such as Galileo, Newton, and Huygens, and lesser-known craftsmen and amateurs who played pivotal roles in advancing telescope technology. King's narrative is enriched by nearly 200 illustrations, including portraits, diagrams, and photographs, offering readers a visual journey through the evolution of astronomical instruments. The book is praised for its detailed scholarship and accessibility, making it a valuable resource for both enthusiasts and scholars interested in the history of astronomy and optical science.

Cheng in his book [1] offers a comprehensive exploration of telescope design across the electromagnetic spectrum, including radio, infrared, optical, X-ray, and gamma-ray wavelengths. Drawing from over twenty-five years of experience, Cheng provides both a general introduction and an in-depth theoretical analysis of telescope design. The book is structured into several chapters, each focusing on different aspects of telescope design. Bely [2] offers a comprehensive resource that consolidates the astronomical and engineering principles essential for designing and building large telescopes. Published in 2003 as part of the Astronomy and Astrophysics Library series, the book addresses various aspects of telescope development, from fundamental astronomical observations to detailed engineering considerations. Rutten and van Venrooij's [3] excellent book explains the principles and practicalities of telescope design and performance, tailored specifically for amateur astronomers. First published in 1988, this book serves as both an educational resource and a reference manual. Schroeder's [4] book is a comprehensive text that delves into the fundamental principles and applications of optical design in astronomy. The book offers a unified treatment of various types of telescopes, addressing both those influenced by geometrical aberrations and atmospheric effects, as well as diffraction-limited telescopes intended for space-based observations. Emphasizing foundational concepts like Fermat's principle, Schroeder applies these to optical systems crafted for imaging distant celestial bodies. Wilson in his two-volume series [5,6] provides an in-depth exploration of the design, manufacture, and testing of reflecting telescopes. The first volume offers an overview of the optical theory and historical evolution of reflecting telescope systems. It covers fundamental design principles, including Gaussian optics and aberration theory, and discusses field correctors and focal reducers. The book also provides a historical perspective, detailing major telescopes from Lord Rosse's era up to the 1980s. Building upon the first volume, volume II delves into modern developments in reflecting telescope optics over the past two decades. It addresses advancements in manufacturing and testing procedures, alignment techniques, and the integration of active control systems in telescopes. Topics such as atmospheric and adaptive optics, reflecting coatings, and ancillary equipment are also explored. Hardy's [35] book provides an introduction to adaptive optics (AO) technology, which is used to correct distortions caused by atmospheric turbulence in astronomical observations. It covers fundamental AO principles, wavefront sensing, deformable mirrors, and real-time control systems. The book is essential for researchers, engineers, and astronomers working on high-resolution imaging. In Report No. 90 [39], one can find the optical design details of the 10-meter telescope used in Keck Observatory, among other things discussed. Walker's [7] book is a comprehensive guide that bridges the fields of optical engineering and human vision; it shows the intricate relationship between optical instruments and the human eye, providing both theoretical insights and practical design considerations. Throughout the book, Walker combines clear explanations with practical examples, making complex concepts accessible to both students and practicing engineers. Geary [8] wrote a useful book (based on an introductory lens design course from the Optical Science & Engineering doctoral program at the University of Alabama in Huntsville) dealing with lens design, rich with practical work (Ansys Zemax). The book offers a large number of illustrations, numerous examples, and problem solutions, making it suitable for both self-study and as a comprehensive introductory text. Smith's [9] book is a comprehensive guide that delves into the methodologies and applications of designing optical systems using computer-aided tools. Throughout the book, Smith adopts a practical and intuitive approach, minimizing complex mathematics to make the content accessible. The inclusion of numerous illustrations and problem solutions enhances comprehension, making it suitable for self-study or as a course textbook. O'Shea and Bentley [10] wrote an excellent book that demonstrates the process of designing optical systems using Ansys Zemax, a leading optical design software. Published in 2024, this book offers a step-by-step approach to different lens designs, from initial definition through performance analysis and tolerancing. Korsch's [70] "Reflective Optics" is a foundational book focusing on the theory, design, and practical applications of reflective optical systems, especially those used in astronomical telescopes, space optics, and high-resolution imaging systems. Unlike refractive optics, reflective systems rely entirely on mirrors, which are important in situations where chromatic aberration must be avoided or where wide wavelength ranges are used. Oswalt made [71] is a comprehensive book that offers an in-depth exploration of the instruments and techniques that have revolutionized our understanding of the universe, and encompasses a wide range of topics, from traditional optical telescopes to cutting-edge space-based observatories, providing readers with a holistic view of contemporary astronomical instrumentation.

Among several books in the field of amateur telescope-making, a few dozen stand out. Suiter's [11] book is a comprehensive guide that delves into the star test method, a powerful technique for assessing and diagnosing the optical performance of different telescopes directly under the night sky. This manual is particularly valuable for amateur astronomers and telescope enthusiasts seeking to evaluate and enhance their instruments without relying on complex equipment. Allan Mackintosh compiled [12,13] a two-volume series, based on selected articles from the Maksutov Circulars, a newsletter distributed over 21 years to members of the Maksutov Club. These volumes serve as guides for amateur and professional telescope makers, offering in-depth insights into both the optical and mechanical aspects of telescope construction and enhancement. Texereau [14] wrote a classic guide for amateur telescope makers. The book provides step-by-step instructions on grinding, polishing, and testing telescope mirrors, as well as constructing telescope mounts and other essential components. It covers optical theory, material selection, and practical techniques to help enthusiasts build high-quality reflecting telescopes. The book remains a fundamental resource for those interested in hands-on telescope fabrication. Tonkin [15] edited a guide that compiles practical knowledge and techniques for constructing telescopes. It includes contributions from experienced telescope makers, covering topics such as grinding and polishing mirrors, assembling mounts, and optimizing optical performance. The book provides step-by-step instructions, technical insights, and hands-on guidance for hobbyists looking to build and refine their telescopes. It serves as an essential resource for amateur astronomers and DIY telescope enthusiasts. Clark [16] provided a practical guide for modern-day telescope makers, focusing on how to leverage the internet for sourcing materials, obtaining advice, and connecting with the global community of amateur astronomers. The book provides insights into using online resources to find parts, tools, and information for building telescopes, as well as how to troubleshoot and get expert help. It also includes tips on joining online forums, participating in virtual workshops, and using digital tools for design and testing. Jim and Dennis Kriege [17] wrote a comprehensive guide to building and using Dobsonian telescopes, which are known for their simplicity, stability, and excellent performance in amateur astronomy. The book covers everything from the basic principles of telescope design to step-by-step instructions on constructing a Dobsonian mount and optimizing the optical system. It provides practical advice on materials, tools, and techniques, making it an invaluable resource for amateur astronomers interested in creating their own large, easy-to-use telescopes. Ingalls [18,19,20] wrote three volumes, each offering practical guidance on designing, building, and testing telescopes, primarily aimed at amateur astronomers. Volume 1 introduces the basics of telescope making, focusing on mirror grinding and polishing techniques. It also covers the construction of the telescope mount and the assembly of the optical system. Volume 2 delves into more advanced techniques, including complex mirror designs, multi-element telescopes, and methods to improve optical performance. It emphasizes precision in crafting larger telescopes and finer optics, ideal for those with some experience in telescope making. Volume 3 focuses on the construction of large telescopes, particularly those intended for serious amateur astronomical observation. It covers topics like large mirror making, sophisticated mounting systems, and fine-tuning optical performance for high-resolution astronomy. This volume is more technical and geared toward advanced hobbyists. Remer [21] wrote a practical guide designed for amateur astronomers interested in constructing their own refractor telescopes. The book provides detailed instructions on how to craft high-quality optics, including lens making and alignment, as well as the construction of the tube and mounting system. It also covers the necessary tools and materials, giving step-by-step guidance on achieving a well-optimized refractor for both visual observation and astrophotography. Highe [22] gave a practical guide aimed at amateur astronomers who wish to build or optimize portable Newtonian telescopes. His book covers various aspects of telescope design, from choosing the materials and optics to constructing a stable, lightweight mount. It focuses on creating a telescope that is both easy to transport and capable of providing high-quality views for deep-sky observing. The book also includes tips for achieving optimal performance and providing advice on modifications to improve portability without compromising optical quality. Daley's [23] book provides a detailed exploration of the Schupmann telescope design, an optical system that offers a combination of wide-field viewing and high-quality imaging. The book focuses on how this design works, its optical advantages, and the engineering involved in constructing such telescopes. Daley covers the theoretical foundation behind the Schupmann design, as well as practical guidance on building and fine-tuning these telescopes. This is useful for amateur astronomers looking to explore a unique and less common optical design.

For information on amateur telescope optics, one should also visit the following websites: *Amateur Telescope Optics* [40] by V. Sacek (this site offers detailed insights into telescope design, optical theory, and practical advice for enthusiasts), *Telescope Optics Topics* [41] by B. Greer (a repository of personal research focusing on Newtonian telescope design, including articles and companion pages for magazine features), *Astronomical optics* [155], *Telescope Optics for Hobbyists* [42] by Edmund Optics (provides guidance on building telescopes, understanding different types, and selecting appropriate components), as well as online forums, such as one at *Cloudy Nights astronomical community* [43].

2.1. Review of scientific papers

The field of astronomical telescope design is supported by an extensive and growing body of scholarly work, comprising hundreds of high-quality research papers and technical articles. Given the sheer volume of publications, it is challenging to isolate and highlight individual contributions without overlooking many others of significance. Consequently, this review selectively presents a representative subset of the literature, focusing on papers that offer valuable insights into key design principles, innovations, and emerging trends in telescope technology.

While this selection does not claim to be exhaustive - due to the breadth and diversity of research in the field - it aims to provide a meaningful overview of current research directions and foundational studies in this area. By drawing from a variety of sources, this review captures the multifaceted nature of telescope design, encompassing optical theory, material science, engineering challenges, and practical applications for both amateur and professional astronomy. The curated list serves not only to illustrate the state of the art but also to identify areas where ongoing research is actively pushing the boundaries of telescope performance and usability.

Pease's 1935 paper, "Modern Large Telescope Design" [24], published in the Journal of the Optical Society of America, delves into the advancements and methodologies in constructing large-scale optical telescopes. Pease, a pivotal figure at the Mount Wilson Solar Observatory, contributed significantly to the design of major instruments, including the 100-inch Hooker Telescope and the 200-inch Hale Telescope. His expertise in astronomical instrument design has been instrumental in shaping modern observational astronomy. Feinberg et al. [25] published an overview of the multifaceted factors influencing the design of astronomical space telescopes. It introduces performance metrics that translate scientific goals into design requirements and discusses cost estimation factors such as mass, complexity, technology maturity, and heritage. The authors aimed to provide a roadmap for future space telescope designers to optimize designs that enhance scientific capabilities while minimizing total costs.

Endelman [26] provides an overview of the Hubble Space Telescope (HST), from its inception through its early challenges, design, and subsequent remedies. Launched in April 1990 after nearly fifteen years of development, the HST aimed to advance our understanding of the universe by observing celestial phenomena without atmospheric interference. However, initial images revealed a significant issue: the primary 2.4-meter mirror suffered from spherical aberration due to a manufacturing flaw, leading to blurred images. Additional complications arose with the solar arrays, guidance systems, and auxiliary equipment. To address these issues, an 11-day servicing mission commenced on December 2, 1993, during which astronauts aboard the Space Shuttle Endeavour replaced and repaired malfunctioning components.

McElwain et al. [27] discuss the design, development, and in-orbit performance of the Optical Telescope Element (OTE) of the James Webb Space Telescope (JWST). Key points covered in the paper are design and architecture, alignment and wavefront sensing, deployment and commissioning, as well as performance and scientific impact. Regarding JWST, Contreras and Lightsey [28] also provided a review of the mission optical requirements and optical architecture. They described the telescope design, highlighted some of the features of the baseline telescope, and discussed the nominal performance. In addition, their paper provided an overview of the wavefront sensing and control process and described some of the special optical analysis considerations necessary in a system needing remote, on-orbit alignment.

Parshley et al. [29] presented a common optical design for a 6-meter aperture, crossed-Dragone telescope adopted by both the CCAT-prime and Simons Observatory projects. The design offers a high-throughput, relatively flat focal plane with a 7.8-degree field of view at 3 mm wavelengths, suitable for submillimeter and millimeter observations.

Huiru Ji et al [30] proposed a method to design a high-throughput telescope using an off-axis Three-Mirror Anastigmat configuration combined with a scanning mechanism. The resulting design achieves an F-number of 6, a 60° × 1.5° field of view, and a focal length of 876 mm, making it suitable for optical remote sensing applications. Sirsi et al [31] discuss the design of OASIS, a proposed space telescope featuring a 14-meter inflatable primary reflector. The telescope is intended for high spectral resolution observations in the terahertz frequency range, utilizing aberration correction optics and a scanning mechanism to achieve a 0.1-degree field of regard with diffraction-limited performance.

Graves et al [32] paper addresses the integrated design and manufacturing processes of next-generation large telescopes. It covers topics from optical design to enclosure requirements, emphasizing the need for novel approaches to meet the scientific goals of future observatories. Muslimov et al [33] present the design of an all-reflective, bi-folded Schmidt telescope aimed at surveying extended astronomical objects with extremely low surface brightness. The innovative design incorporates a curved detector to achieve high image quality over a large field of view, making it suitable for deep-sky surveys.

Zhang et al [34] studied the conceptual optical design of a 6.5-meter wide-field survey telescope. The design emphasizes excellent image quality across a broad field of view, aiming to facilitate large-scale astronomical surveys with high efficiency. Ho Jin et al. [35] presented the development of a compact reflecting telescope tailored for a 3U CubeSat platform, aiming to capture high-quality Earth imagery. The authors designed a Ritchey-Chrétien type telescope with off-axis segmented mirrors. At an operational altitude of 700 km, the system can image approximately a 4 km by 2.3 km area of Earth's surface. This design demonstrates the feasibility of integrating high-resolution reflecting telescopes into CubeSat missions, offering a resilient alternative to lens-based systems.

Catalan [36] introduces approximate formulas to quantify axial coma resulting from surface tilt and decentering, as well as spherical aberration due to axial displacement. These formulas distinguish between aberrations induced by preceding subsystems and those intrinsic to the misaligned surface. This differentiation offers a straightforward approach to designing telescopic systems less sensitive to specific misalignments. Catalan applies this method to a two-mirror astronomical telescope with a corrector, demonstrating significant reductions in sensitivity to tilt and despace misalignments. The paper also discusses the limitations of these solutions and the challenges in simultaneously correcting multiple misalignment types.

Stepp and Strom [37] provide an overview of the initial design and development efforts for the Thirty Meter Telescope (TMT) project. The TMT aims to construct a 30-meter diameter optical-infrared telescope to enable groundbreaking astronomical observations. The authors discuss key aspects of the project, including the scientific objectives driving the telescope's design, the technical challenges associated with constructing such a large segmented mirror system, and the adaptive optics required to achieve diffraction-limited performance. They also outline the collaborative efforts among various institutions and the planned timeline for the project's development phases.

K. W. Hodapp and colleagues [38] presented the development of the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), initiated by the University of Hawaii's Institute for Astronomy. The primary goal of Pan-STARRS was to detect potentially hazardous asteroids (PHAs) and conduct comprehensive sky surveys. The design emphasizes a wide field of view and rapid sky coverage, utilizing a large aperture and advanced optical components to achieve high image quality across a broad field. The paper details the optical design choices, including the configuration of mirrors and corrector elements, to meet the scientific objectives of asteroid detection and sky surveying.

Macias et al. [65] present a student-led initiative to design, fabricate, and evaluate a low-cost Newtonian telescope using 3D printing technology. The primary objectives were to assess the feasibility of constructing functional telescopes with additive manufacturing and to develop educational resources that facilitate hands-on learning in astronomy and engineering.

Abdulrahman et al. [66] investigated how the positioning of the secondary mirror affects the optical performance of Maksutov–Cassegrain telescopes. Utilizing Zemax optical design software, the study models and analyzes two configurations (A and B). Design A features a secondary mirror affixed directly to the inner surface of the Maksutov corrector lens. Design B employs a separate secondary mirror positioned between the corrector lens and the primary mirror, not attached to the lens. The study concludes that the configuration where the secondary mirror is not attached to the Maksutov corrector lens (Design B) offers superior optical efficiency and image quality. This design choice reduces aberrations and enhances overall performance, making it a preferable option for applications requiring high-precision imaging.

Hasan [67] presents a comprehensive analysis of the optical performance of a Schmidt-Cassegrain telescope (SCT) design, with a particular focus on the effects of spider obscuration. Utilizing Zemax optical design software, the study aims to assess how the structural components, specifically the spider vanes supporting the secondary mirror, influence image quality.

Aljizany [68] explores the enhancement of the Hubble Space Telescope's optical performance through the integration of nano-sensor technology at the eyepiece. Utilizing the Zemax optical design software, the study simulates the telescope's optical system to assess the impact of nano-sensors on image quality. Alcant [69] presents a study on the design and simulation of a terrestrial refractive binocular telescope with adjustable effective focal length. It was investigated how changes in the effective focal length impact image quality and overall optical performance.

Other relevant papers, regarding the design of the astronomical telescope, with emphasis on amateur design, can be found in references [70-153].

3. Image quality considerations

The performance of an optical system is primarily influenced by the aberrations inherent in its design. These aberrations are categorized into two main types:

1. Monochromatic Aberrations: These occur when light of a single wavelength passes through the system. They are present in both refracting and reflecting optical systems.
2. Chromatic Aberrations: These arise due to the dispersion of light, where different wavelengths are refracted by varying amounts, leading to focus discrepancies. Chromatic aberrations are exclusive to systems containing refractive elements.

When aberrations are present in the image, the image of a point source becomes a blur, known as the "scattering figure" or "blur circle." This blur results from a combination of various aberrations rather than a single type.

The primary monochromatic aberrations include:

- Spherical Aberration: Occurs when light rays parallel to the optical axis enter the system at different heights and converge at different points along the axis. This can be mitigated by restricting the aperture, though it may reduce light-gathering capacity.
- Coma: Manifested as a comet-shaped blur, coma arises when off-axis light rays do not converge at the same point, leading to asymmetric image blurring. It is particularly problematic in astrophotography, as it distorts star images, making precise measurements challenging.
- Astigmatism: This aberration occurs when light rays in different planes (tangential and sagittal) focus at different points, resulting in an image that is sharp in one direction but blurred in another.
- Field Curvature: Refers to the phenomenon where the image is sharp only on a curved focal plane, not on a flat one. Using a flat sensor or photographic plate leads to unsharp images at the periphery. This can be corrected by employing field flatteners or using curved photographic films.
- Distortion: Unlike other aberrations, distortion affects the image scale rather than sharpness. Positive distortion (pincushion) causes straight lines to bend inward, while negative distortion (barrel) causes them to bulge outward.

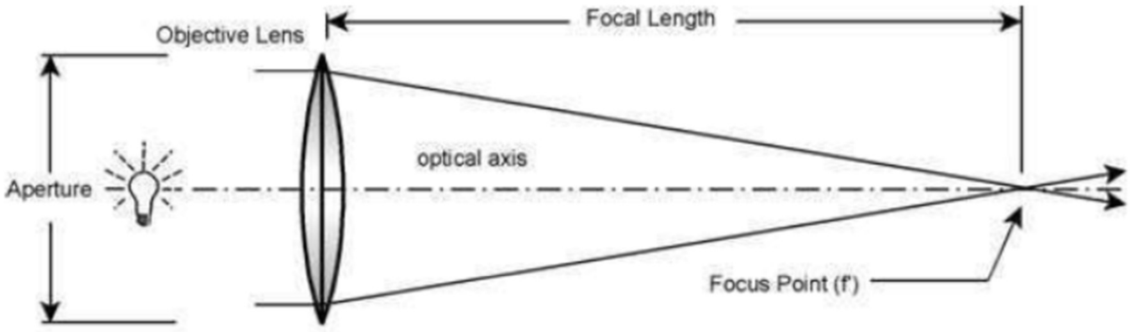
3.1 Image quality criteria

Image quality criteria for telescopes refer to the set of factors and parameters that determine how well a telescope can produce clear, sharp, and accurate images of celestial objects. Here are the key criteria commonly used to evaluate telescope image quality:

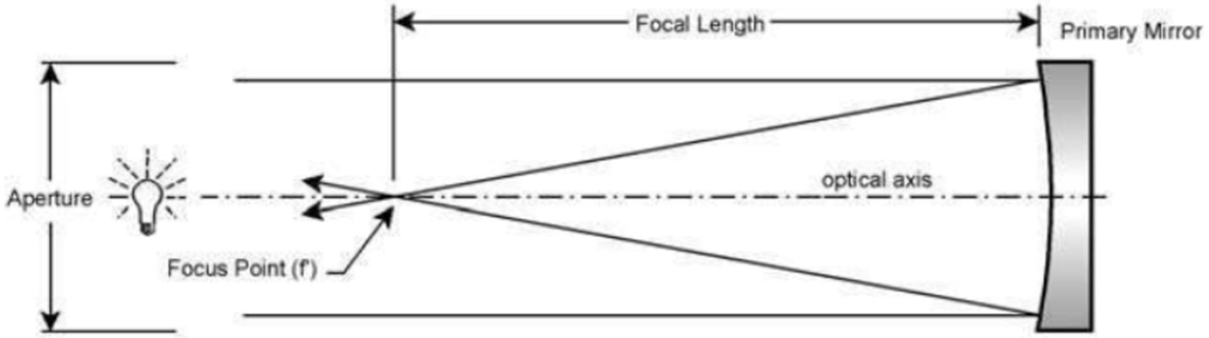
1. Resolution
    - The ability to distinguish fine detail and separate closely spaced objects. Limited by the telescope’s aperture and affected by diffraction.
2. Contrast
    - The ability to display differences in brightness between features. High contrast is important for observing faint objects near bright ones.
3. Aberration Control
    - Minimizing optical defects such as chromatic aberration, spherical aberration, coma, astigmatism, and field curvature.
4. Field of View (FOV)
    - The angular size of the sky visible through the telescope; wider FOVs are better for extended objects or star fields.
5. Light Gathering Power
    - The amount of light collected, primarily determined by aperture size, impacts brightness and detail visibility.
6. Diffraction Limit
    - The fundamental limit on resolution caused by light diffraction defines the best possible image sharpness.
7. Image Brightness
    - Related to aperture and focal ratio, affecting the visibility of faint details.

8. Point Spread Function (PSF) and Airy disk size
    - Describes how a point source (like a star) is imaged; a smaller and more concentrated PSF means sharper images.
9. Mechanical and thermal stability
    - Stability affects focus consistency and image sharpness, as vibrations or temperature changes can degrade image quality.
10. Optical coatings and transmission
    - Quality anti-reflective coatings improve light throughput and reduce ghosting or flare.

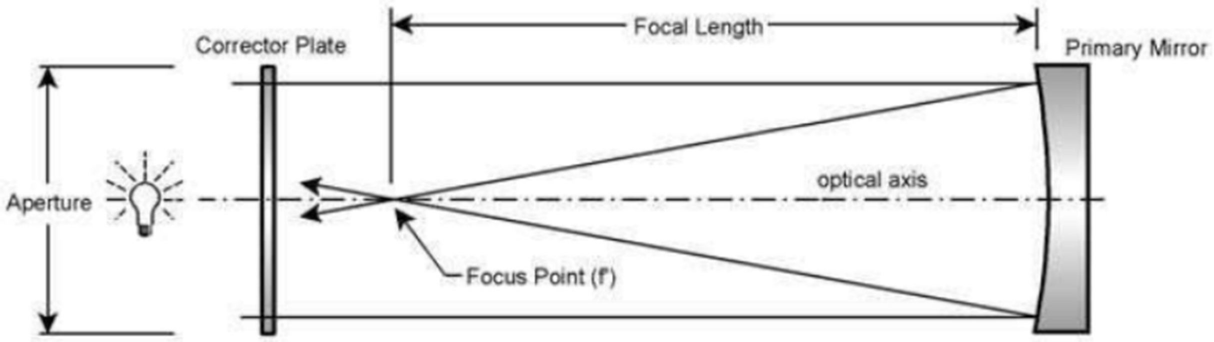
The three main types of astronomical telescopes mentioned here - refractors, reflectors, and catadioptric systems (Fig. 1) - each have distinct optical designs that influence their image quality based on the criteria outlined above.



(a) Lens system (refractor)



(b) Mirror system (reflector)



(c) Mirror/Lens system (catadioptric)

Fig. 1 Scheme of refracting, reflecting and catadioptric telescope design [154]

Refractors use lenses to gather and focus light, offering high contrast and excellent mechanical stability due to their sealed tube design. They generally produce sharp, high-resolution images with minimal maintenance. However, they are prone to chromatic aberration, where different wavelengths focus at slightly different points, resulting in color fringing unless corrected by achromatic or apochromatic lens combinations. Refractors often have a relatively narrow field of view and can be expensive at larger apertures due to the complexity and cost of high-quality lens glass and coatings.

Reflectors use mirrors, eliminating chromatic aberration since reflection is wavelength-independent. This allows for larger apertures at lower costs, resulting in superior resolution and light-gathering power, key advantages for deep-sky observation and astrophotography. However, reflectors can suffer from spherical aberration if mirrors are not precisely shaped and aligned. They may also exhibit coma and require regular collimation to maintain optical alignment. Reflectors typically have open tubes, which can lead to thermal currents affecting image stability.

Catadioptric telescope designs combine lenses and mirrors to capitalize on the benefits of both systems while minimizing their weaknesses. These hybrid telescopes offer compact form factors and improved correction of aberrations, including reduced coma and spherical aberration. Their optical coatings and design often provide good contrast and wide fields of view, making them versatile for both planetary and deep-sky imaging. However, their complex optical path can often lead to some light loss and require more precise manufacturing and alignment. Generally, catadioptrics often have moderate focal ratios, balancing image brightness and field of view.

Telescopes have three main roles [155]:

- Light gathering & compression: They collect much more light than the eye, making faint objects visible. This gathered light is then focused into a smaller beam that can enter the eye or fit onto a sensor.
- Angular resolution & magnification: Telescopes resolve fine details by having a much wider "pupil" than the eye. They then magnify this detailed image so the eye can see it, while the increased light grasp keeps the image bright enough.
- Pointing & tracking: Telescopes can be aimed at any point in the sky and can follow celestial objects as the Earth rotates, often using motorized mounts with computer control.

Important optical characteristics of telescopes are [155]:

1. Aperture: determines light-gathering ability (fainter objects visible), image resolution (finer detail), the impact of atmospheric turbulence ("aperture seeing"), and partly the telescope's weight and size.
2. Focal length: Primarily dictates the telescope's magnification. Longer focal lengths yield higher base magnification. In visual use, it sets the magnification range achievable with different eyepieces. It also influences the telescope's physical length.
3. Focal ratio (relative aperture): Affects image brightness; faster (lower number) ratios concentrate more light per area. It also determines the image scale for astrophotography.

3.2 Spot diagrams

Spot diagrams are one of the fundamental analytical tools used in optical design. They are used to simulate and visualize the distribution of light from a point source as it appears on the telescope's focal plane. By plotting the positions where rays of light converge, spot diagrams effectively illustrate the size, shape, and intensity pattern of the resulting image. These diagrams can provide a clear graphical representation of the impact of various optical aberrations, such as spherical aberration, coma, and astigmatism, on image quality.

By examining spot diagrams, optical designers can assess the degree to which aberrations distort the ideal point image, evaluate the effectiveness of corrective measures, and optimize lens or mirror configurations to achieve sharper, more accurate images. In this way, spot diagrams serve as a critical diagnostic tool in the iterative process of refining telescope optics to meet desired performance standards.

For visual observation, especially at high magnifications, the spread of spots in the focal plane should be minimal. Typically, 90 to 95% of the rays should be concentrated within a circle no larger than the Airy disk. An Airy disk is the central bright spot in the diffraction pattern formed when light passes through a circular aperture, like a telescope lens. It represents the smallest point to which a perfect optical system can focus light, setting the limit of resolution due to diffraction. The Airy disk's diameter depends on the focal ratio of the objective and the wavelength of light.

For astrophotography, the image quality is traditionally determined by the resolving power of the photographic emulsion. Research indicates that the smallest star images on professional astrophotographic plates have diameters no smaller than 0.025 mm [3].

4. Refracting (dioptric) telescopes

Refractor telescopes (Fig. 1), among the earliest optical instruments designed for astronomical observation, utilize lenses to gather and focus light, producing magnified images of distant objects. Invented in the early 17th century, these telescopes have evolved significantly, finding applications in astronomy, terrestrial observation, and optical research. The fundamental principle of a refractor telescope involves the refraction of light through a convex objective lens to form a real image, which is then magnified by an eyepiece.

The history of refractor telescopes begins with Hans Lippershey, who patented the first refracting telescope in 1608, though Galileo Galilei popularized its use in astronomy shortly thereafter with his improved designs [44]. Early refractors suffered from chromatic aberration, a distortion caused by the varying refraction of different wavelengths of light, resulting in colored fringes around observed objects [45]. Sir Isaac Newton’s work on optics in the late 17th century highlighted these limitations, prompting the development of achromatic lenses by Chester Moore Hall and John Dolland in the 18th century [46]. These lenses, combining crown and flint glass, significantly reduced chromatic aberration, enhancing image clarity [47].

In the 19th century, advancements in glass manufacturing and lens grinding, as documented by Joseph Fraunhofer, allowed for larger objective lenses with improved light-gathering capabilities [48]. Fraunhofer’s work on apochromatic lenses, which correct for three wavelengths of light, further refined refractor performance. Modern literature, such as Born and Wolf’s *Principles of Optics*, provides a detailed theoretical framework for understanding lens aberrations and their correction in refractor designs [49]. Recent studies explore the integration of adaptive optics and digital imaging in refractors, expanding their utility beyond traditional astronomy.

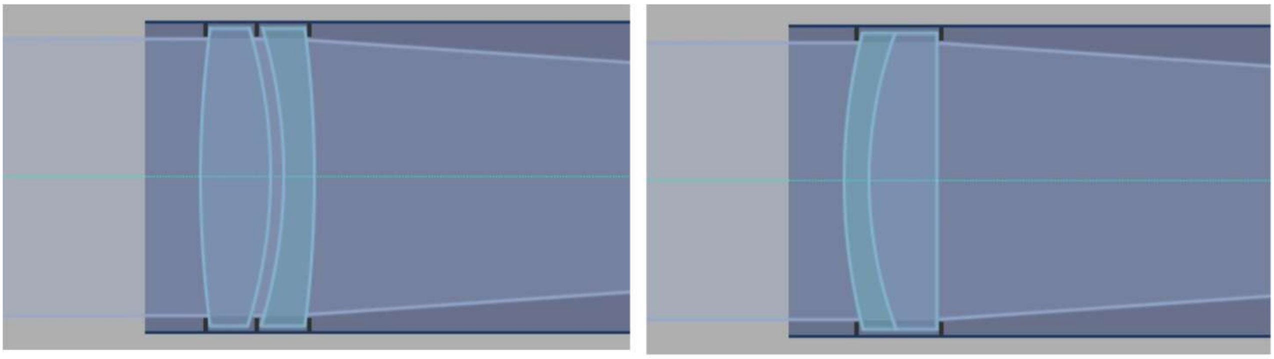
The design of a refractor telescope involves several key components: the objective lens, the tube assembly, the focuser, and the eyepiece. Each element requires precise engineering to optimize performance.

4.1 Objective lens design

The objective lens is the heart of a refractor telescope, determining its light-gathering power and resolution. The lens’s focal length (f) and aperture (D) dictate the telescope’s magnification and field of view, calculated as $M=f_{objective}/f_{eyepiece}$. To minimize chromatic aberration, modern refractors employ achromatic or apochromatic lens systems. An achromatic doublet (Fig. 2) typically pairs a convex crown glass lens (low dispersion) with a concave flint glass lens (high dispersion), aligning red and blue wavelengths at a common focal point [50].

Early achromatic refractors, developed around 1760 by John Dollond and Jesse Ramsden, featured small doublet lenses (aperture ~130 mm). Advances in flint glass production by Pierre Louis Guinand enabled Joseph von Fraunhofer to design a larger 240 mm air-spaced doublet (Fig. 2), first used in the Dorpat refractor. This Fraunhofer doublet, with a crown and flint lens separated by a small air gap, offered four optical surfaces to correct chromatic and spherical aberration, as well as coma. Optimal performance is usually achieved at focal ratios between $f/10$ and $f/20$, with faster ratios used for wide-field applications like astrophotography.

The Steinheil achromatic doublet (Fig. 2) positions the flint glass element at the front and the crown glass at the rear, unlike the more common Fraunhofer design. This configuration requires stronger lens curvatures and typically features a narrower air gap between the elements. While it offers improved correction of optical aberrations, its use is limited due to the flint glass's susceptibility to atmospheric moisture, which can lead to degradation such as spotting or opacity over time [155].



Fraunhofer achromat design

Steinheil achromat design

Fig. 2 Scheme of refracting achromatic designs (Fraunhofer and Steinheil) [155]

In Table 1 are given several other achromat doublet designs as well, presented in [40]. These specifications are for 100 mm aperture, $f/10$ lenses. However, they can be adapted for refractors with similar apertures, ranging from about 50% faster to slower focal ratios. This scaling is done by directly applying the desired focal ratio to the given radii, requiring only small ray tracing tweaks. Similarly, swapping out comparable glass types should only need minor adjustments. Glass thickness isn't a concern, except in the case of Gauss-type.

Table 1. Achromat doublets designs, general specifications for BK7/F2 glass (in units of focal length) [40]

Type	**Aplanat**	**R_1**	**t_1**	**M_1**	**R_2**	**Air (M_2)**	**R_3**	**t_3**	**M_3**	**R_4**
Fraunhofer	Yes	0.6	0.011	BK7	-0.36	0.001	-0.363	0.007	F2	-1.51
Steinheil	Yes	0.442	0.007	F2	0.229	0.001	0.2285	0.009	BK7	-15
Baker	Yes	0.582	0.011	BK7	-0.363	0.003	-0.363	0.007	F2	-1.59
Littrow	No	0.45	0.01	BK7	-0.45	0.00005	-0.45	0.006	F2	-7.7
Clark	No	0.428	0.01	BK7	-0.428	0.015	-0.4	0.0065	F2	-8
Gauss (f/14 and slower)	Yes	0.129	0.00665	BK7	0.3345	0.0003	0.14206	0.0042	F2	0.10357
Cooke	No	0.373	0.009	BK7	-0.563	0.001	-0.527	0.006	F2	4.7

Apochromatic lenses (Fig. 3), often triplets, incorporate an additional element (e.g., extra-low dispersion glass) to align three wavelengths, reducing residual color aberration [51].

Invented in 1840 by Hungarian optician Joseph Petzval, this apochromatic lens (f/4 – f/6) design uses two separated doublets (one cemented, one not). Initially a fast portrait lens (around $f/4$) for early photography, its doublets can be refined for telescopes to minimize color distortion across a wider field (about 5°). Petzval lenses produce a sharp center but have curved and distorted edges. The lens's aperture creates a characteristic blurred background (bokeh) seen in 19th-century portraits. Astronomer E.E. Barnard used a Petzval for Milky Way photos, leading to versions specifically made for astronomy, like Tele Vue's design.

By the late 1800s, more diverse optical glasses enabled Ernst Abbe and Peter Rudolph at Zeiss to create apochromatic microscope lenses in 1890. However, H. Dennis Taylor at Cooke & Sons patented the first large triplet lens with apochromatic qualities in 1892. This "Cooke triplet" design (f/4 – f/6), using a crown lens doublet paired with a negative flint to balance dispersion, is the foundation for modern apochromatic lenses.

Today's apochromatic refractors are usually triplet lenses (air, oil, or cemented) initially made with synthetic fluorite for the crown element and two high-dispersion flint glasses. The specific glass types significantly impact both optical quality and lens lifespan. Air-spaced designs include screws for precise alignment (centering and collimation). The first modern commercial apochromats were Takahashi's TS series, using synthetic fluorite. In 1981, Astro-Physics (Roland Christen) introduced an oil-spaced triplet using a flint glass initially developed for NASA. A common structure involves a front double convex crown, a middle negative flint, and a rear double convex flint [155].

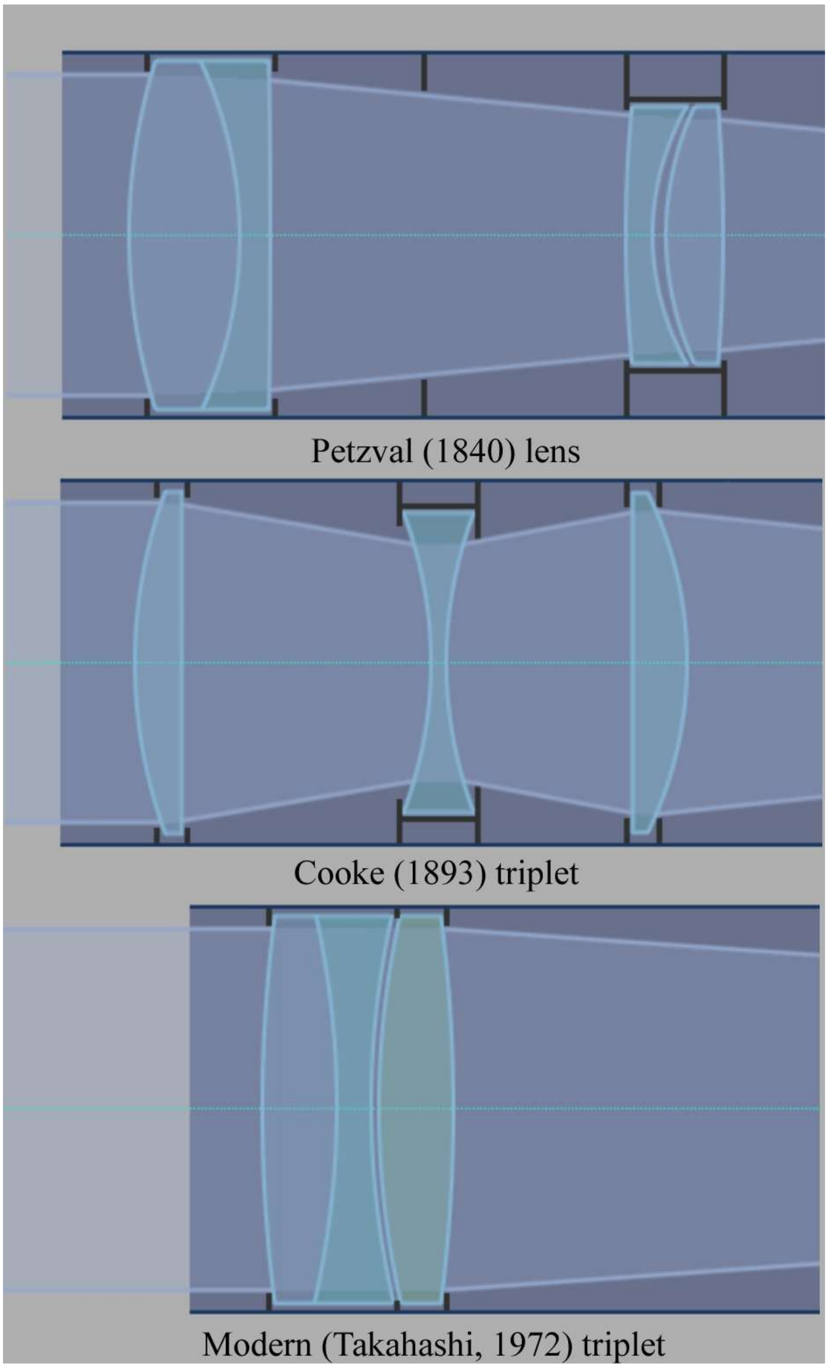


Fig. 3 Scheme of refracting apochromatic designs (Petzval, Cooke, Takahashi) [155]

4.2 Tube assembly

The telescope tube aligns the optical components and shields them from stray light. Its length approximates the focal length of the objective lens, though baffles and coatings are added to reduce internal reflections [52]. Materials like aluminum or carbon fiber are chosen for their rigidity and low thermal expansion, ensuring optical stability across temperature variations.

4.3 Focuser and eyepiece

The focuser adjusts the eyepiece position to achieve sharp focus, typically using a rack-and-pinion or Crayford mechanism for precision. The eyepiece, a secondary lens system, magnifies the image formed by the objective. Common designs include Huygens, Kellner, and Plössl eyepieces, each offering trade-offs in field of view and eye relief. The choice of eyepiece depends on the intended application, with wider fields preferred for deep-sky observation [53]. Eyepieces are usually sold separately and on the market variety exists.

4.4 Testing and optimization

Optical testing, such as the Ronchi or Foucault test, evaluates lens quality by analysing interference patterns or knife-edge shadows [54]. Computer-aided design (CAD) software, like Zemax, simulates light paths to optimize lens spacing and coatings, enhancing transmission and contrast [55].

4.5 Applications

Refractor telescopes serve diverse purposes in both professional and amateur contexts. In astronomy, their high contrast and sharp imaging make them ideal for observing planets, double stars, and lunar details. The apochromatic refractors used in observatories, such as the 1-meter refractor at Yerkes Observatory, exemplify their precision for stellar spectroscopy and astrophotography. Beyond astronomy, refractors are employed in terrestrial observation, such as wildlife monitoring, due to their portability and upright image orientation (with a diagonal prism). In education, small refractors introduce students to optics and celestial navigation, while in research, they contribute to studies of atmospheric optics and light pollution. Their versatility is enhanced by modern adaptations, including digital sensors for real-time imaging.

Refractor telescopes remain a cornerstone of optical technology, blending historical significance with modern innovation. Their design, rooted in the precise manipulation of light through lenses, has evolved from simple Galilean instruments to sophisticated apochromatic systems capable of high-resolution imaging. The methods of design - combining advanced lens crafting, robust mechanical engineering, and optical testing - ensure their continued relevance. While reflecting telescopes dominate large-scale astronomy due to their scalability, refractors excel in clarity and contrast for smaller apertures. Future advancements may integrate adaptive optics and AI-driven image processing, further expanding their capabilities.

4.6 Technical considerations

Refractors suffer from residual chromatic and spherical aberration. This affects shorter focal ratios more than longer ones. An f/6 achromatic refractor is likely to show considerable color fringing (a purple halo around bright objects); an f/16 achromat has much less color fringing. In very large apertures, there is also a problem of lens sagging, a result of gravity deforming glass. Since a lens can only be held in place by its edge, the center of a large lens sags due to gravity, distorting the images it produces. The largest practical lens size in a refracting telescope is around 1 meter. There is a further problem of glass defects, striae or small air bubbles trapped within the glass. In addition, glass is opaque to certain wavelengths, and even visible light is dimmed by reflection and absorption when it crosses the air-glass interfaces and passes through the glass itself. Most of these problems are avoided or diminished in reflecting telescopes, which can be made in far larger apertures and which have all but replaced refractors for astronomical research.

Examples of the largest achromatic refracting telescopes are: Great Paris Exhibition Telescope of 1900 (1.25 m) - dismantled after exhibition, Yerkes Observatory (101.6 cm), Swedish 1-m Solar Telescope (98 cm), Lick Observatory (91 cm), Paris Observatory Meudon Great Refractor (83 cm), Potsdam Great Refractor (80 cm), Nice Observatory (77 cm), John Wall (76.20 cm) dialyte refracting telescope - the largest refractor built by an individual, at Hanwell Community Observatory, 28-inch Grubb Refractor at Royal Greenwich Observatory, (71 cm), Great Refractor of Vienna Observatory, (69 cm), Archenhold Observatory – the longest refracting telescope ever built (68 cm × 21 m), United States Naval Observatory refractor (66 cm), Newall refractor at the National Observatory of Athens (62.5 cm), Lowell Observatory (61 cm).

4.7 Image quality in refracting telescopes

A single lens has multiple optical aberrations, so refractor objectives use multiple elements to reduce them, especially longitudinal chromatic and spherical aberration. Coma should also be minimized across a wide field. Chromatic aberration occurs because different wavelengths of light refract differently. Blue light focuses closer to the lens than green or red. In negative lenses, focal points are virtual and in front of the lens.

Achromatic correction uses two closely spaced lenses: a positive crown glass lens (n ≈ 1.5, low dispersion) and a negative flint glass lens (n ≈ 1.6, high dispersion). The positive lens has lower power and dispersion than the negative one. Bending both lenses reduces spherical aberration and coma. Air-spacing them allows more design flexibility. However, astigmatism and field curvature cannot be corrected in standard achromatic doublets, making them unsuitable for wide-angle, sharp imaging on flat film. Generally, designers can adjust 10 variables - glass types, curvature radii, airspace, element order, and thicknesses - to reduce aberrations.

The difference between red/blue and green focus is called the secondary spectrum (Fig. 4). Fraunhofer-type doublets reduce it to 1/2000 of the focal length, semiapochromats to 1/4000, and with advanced glass to 1/8000. The best correction uses fluorite (n = 1.43, V = 95.6), reducing the secondary spectrum to 1/16000 - but it's very expensive and delicate (prone to weathering).

In conventional doublets, the secondary spectrum is acceptable when the red and blue blurs do not exceed three times the diameter of the Airy disk (in green light). So, the condition for freedom from chromatic aberration is: $f_{min}=0.122D$, where f_{min} is the minimum focal ratio, and D is the aperture diameter. For example, for an aperture of 100 mm, the fastest focal ratio giving full achromatism is f/12.2. In doublets corrected for green light, red light is undercorrected and blue is overcorrected, a wavelength-dependent distortion called spherochromatism. This effect occurs in all cemented and narrow-air-gap doublets but can be managed with wider spacing [3].

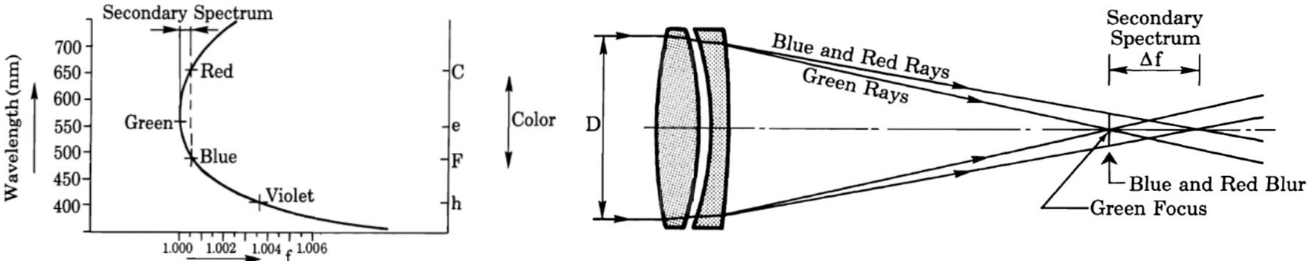


Fig. 4 Color curve for a visually corrected doublet (left); Secondary spectrum in a doublet lens (right) [3]

In [3], a comparison between three 200 mm doublet objectives for refractors, Fraunhofer f/15, cemented Apoklaas f/8, and Fluorite (Steinheil) f/8 types is presented. Fraunhofer design uses standard glass and has the largest color error. Apoklaas uses special glass to halve the secondary spectrum, while the fluorite lens reduces it further, but is sensitive to weathering, so it's placed behind the negative element (Steinheil design). Fluorite lenses allow for faster, shorter telescopes. Design parameters of these refractors are given in Table 2.

Table 2. Design characteristics of three different double refractor designs [3]

Parameter	**Fraunhofer f/15**	**Apoklaas f/10**	**Fluorite *f*/8**
R, Radius of curvature	2009.753	1175.900	546.292
T, Axial dis.	31.336	24	12
M, Medium	517642	487845	720504
R_2	-976.245	-513.920	356.146
T_2	3.315	1	1
M_2	Air	Air	Air
R_3	-985.291	-522.606	348.299
T,	25.109	12	24
M_3	613370	558542	Fluorite
R_1	-3636.839	-2756.828	-6670.445
T_1 Back focal length	2968.12	2000	1599.996
M_1	Air	Air	Air
EFL	3000	2020	1600
1° Field	52.4	35.3	27.9

Note that optical glasses have international standardized six digit code (see Table 2 for medium designations). This indicates the first three digits after the decimal point in the refractive index, n_d, and the first three digits of the Abbe number, v_d. This means that a glass 517642 has a refractive index of 1.517 and an Abbe number of 64.2 (the catalogues show that this glass is BK7, a borosilicate crown glass made by Schott Inc).

The spot diagrams in Fig. 5 show that the Fraunhofer lens has significant color aberration (red/blue spots ~5× the Airy disk). Apoklaas and fluorite lenses show much better correction (~1.5× the Airy disk). However, the fluorite lens, though best for color correction, suffers more from spherochromatism. Despite good visual correction, all these objectives show poor violet correction, especially in photography.

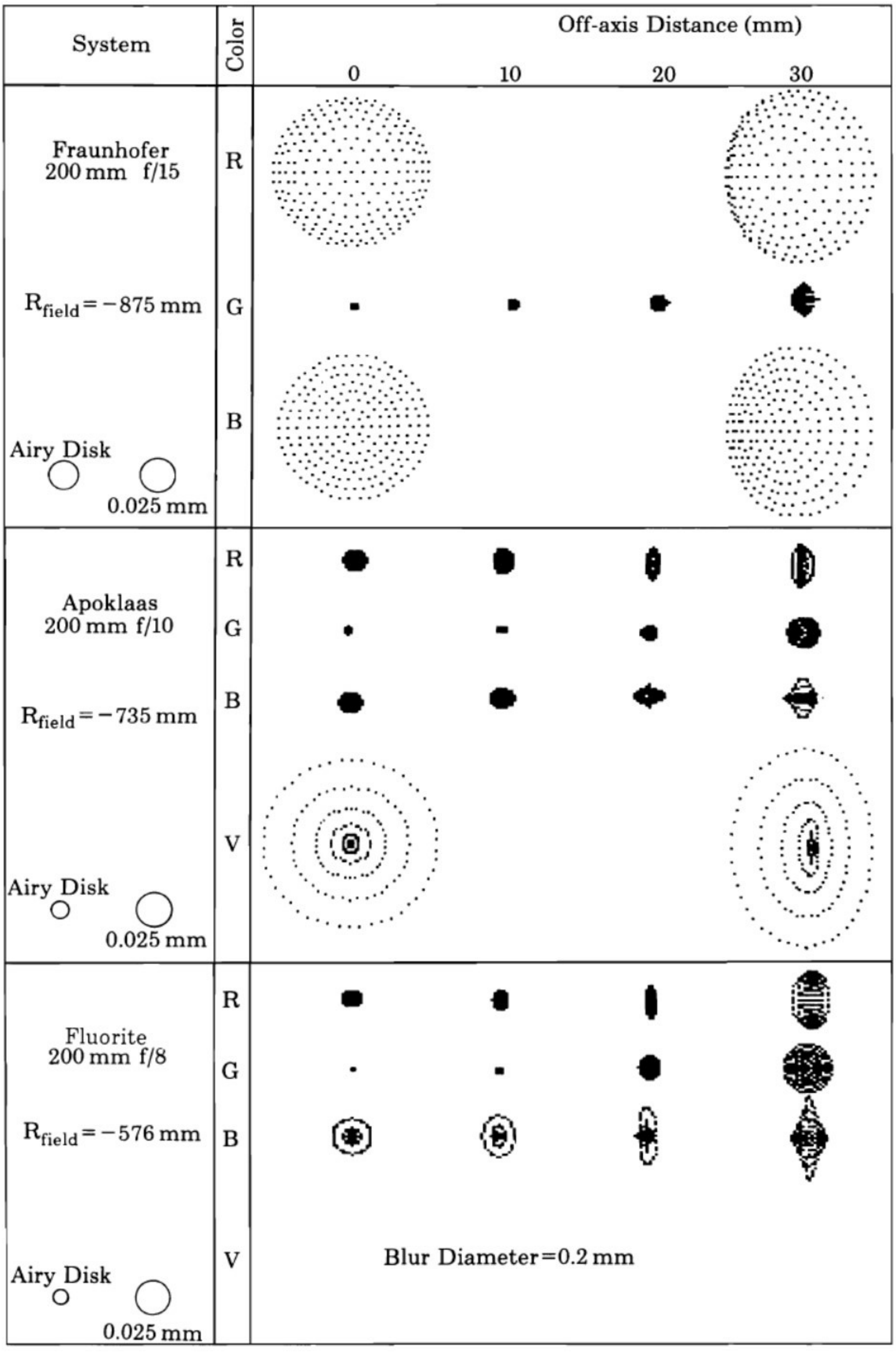


Fig. 5 Spot Diagrams for three 200 mm refractor objectives, as reported in [3]

Regarding previous doublet designs (Table 2 and Fig 5), it can be said that air-spaced lenses allow optimal single-color aberration correction with any glass. Cemented doublets need specific glass pairs with matching curves for best correction (though a small air gap works similarly). A problem with larger (around 100mm+) cemented doublets is that temperature changes can harm the lens bond [40].

To focus red, blue, and violet light together, designers use apochromatic objectives with three lenses made from different materials. These reduce secondary spectrum to about 1/10,000 of the focal length, making them better than achromats for photography [3].

Apochromatic triplets use two crown lenses designed to have a combined dispersion similar to a particular flint glass. While Ernst Abbe defined a true apochromat as a lens with parfocal correction for three distant colors and spherical aberration and coma correction for two, modern "apochromatic" lenses don't fully meet this strict definition. Correcting focus variations across wavelengths (spherochromatism) perfectly requires very long focal lengths, large air gaps, aspherical surfaces, or a Petzval design. Instead, modern lenses minimize spherochromatism using some of these methods, and coma is corrected for one wavelength, which largely reduces it across the visible spectrum.

For wider photographic views and easier portability with shorter tubes, most modern refractors have smaller focal ratios, typically $f/8$ to $f/5$. Special optical glass, known as ED or extra-low dispersion glass, enables more precise lens designs that better minimize both coma and chromatic aberration. Achromatic lenses incorporating ED glass are sometimes sold as ED achromats or semi-apochromats, like those from Sky-Watcher. To control increased optical distortions at higher magnifications, a third lens is incorporated into apochromatic designs, often marketed as APO or APO triplets by companies such as TEC, Astro-Physics, Takahashi, and Sky-Watcher. An even more advanced design uses a fourth lens to create a crown element combined with an ED triplet, referred to as a super apochromat, as nowadays seen in Takahashi's TSA refractors [155].

5. Reflecting (catoptric) telescopes

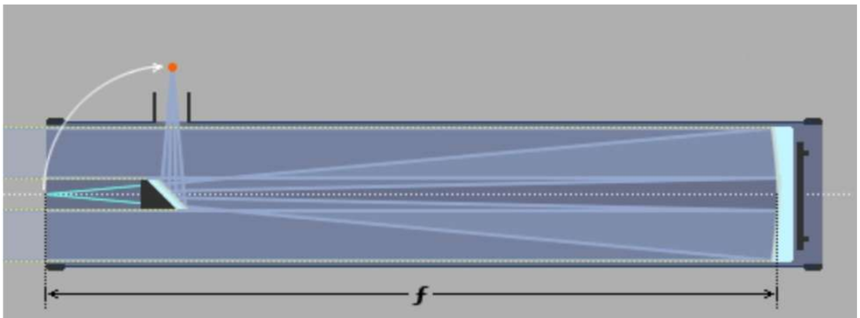
Reflector telescopes (Fig. 1), which employ mirrors to collect and focus light, represent a pivotal advancement in optical astronomy. Unlike refractors, which use lenses, reflectors avoid chromatic aberration, making them ideal for observing faint, distant celestial objects.

The inception of reflector telescopes is credited to Sir Isaac Newton, who constructed the first functional model in 1668 using a concave primary mirror and a flat secondary mirror to redirect light to an eyepiece. Newton’s design addressed the chromatic aberration inherent in refracting telescopes, a problem he identified in his optical studies [45]. In the 18th century, James Gregory proposed an alternative configuration with a parabolic primary mirror and an elliptical secondary mirror, though practical implementation lagged due to manufacturing challenges [56]. William Herschel’s large reflectors in the late 18th century demonstrated the potential of mirrors for deep-sky observation, despite difficulties with speculum metal (a mixture of around two-thirds copper and one-third tin), an alloy prone to tarnishing.

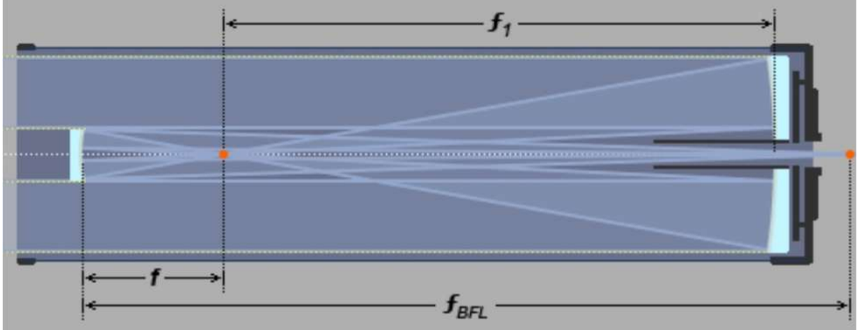
The 19th century saw significant progress with the introduction of silvered glass mirrors by Léon Foucault and the development of parabolic grinding techniques. John Hadley’s work on mirror figuring further refined optical precision, enabling sharper images. In the 20th century, the advent of aluminized coatings, as described by Strong, improved mirror reflectivity and durability [57]. Modern literature provides a rigorous analysis of aberration correction and mirror alignment in advanced designs like the Ritchey-Chrétien telescope [5,6]. Recent studies explore the integration of segmented mirrors and adaptive optics, pushing the boundaries of reflector capabilities.

The design of a reflector telescope hinges on its optical system, structural support, and alignment mechanisms. Key components include the primary mirror, secondary mirror, tube assembly, and mount.

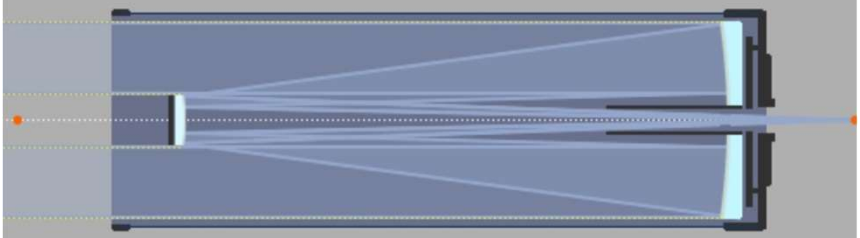
Main types of reflecting telescopes include: Newtonian, Gregorian, Classical Cassegrain, Ritchey Chrétien, Dall Kirkham, as presented in Fig. 6. Parameters in Fig. 6 are: f – effective focal length, f_1 – primary focal length, and f_{BFL} – back focal length.



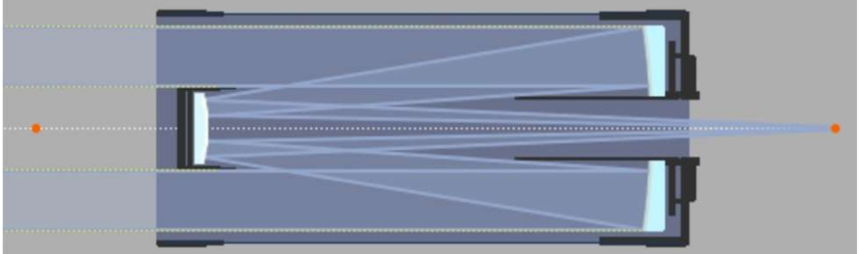
Newtonian (I. Newton, 1680)



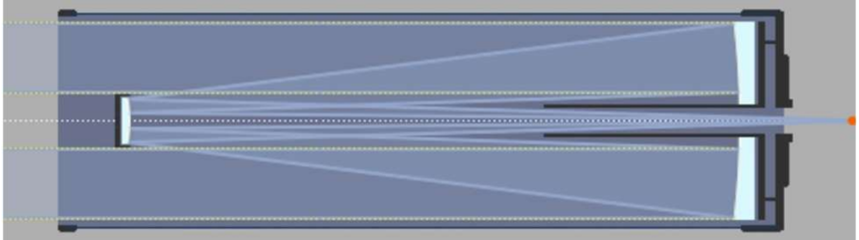
Gregorian (J. Gregory, 1663)



Classical Cassegrain (L. Cassegrain, 1672)



Ritchey-Chrétien (H. Chrétien,1922)



Dale-Kirkham (H. Dall, 1928)

Fig. 6 Main types of reflecting telescopes [155]

The Newtonian reflector (f/4 - f/12), easy to make and with good light grasp, was popular among amateurs for most of the 20th century. Its unfolded light path results in long tubes, typically with focal ratios no faster than $f/10$, though faster ratios are used for light gathering. Astigmatism is eliminated when the focal point is as far from the mirror as the tube opening. Long focal ratio or large aperture Newtonians often require a ladder to reach the eyepiece; the Dobsonian mount with a short focal ratio ($f/5$ or less) can lessen this. At fast focal ratios, coma becomes noticeable but can be lessened with a coma corrector lens. The primary is a paraboloid, and the secondary is flat (plane).

The Gregorian telescope (f/4 – f/40), theorized by Mersenne in 1636 and Gregory later, was first built by Hadley in 1726. It produces an upright image by reflecting light off two mirrors, inverting it twice. This design typically requires a longer tube than a Cassegrain, which is often seen as a disadvantage. Its high magnification makes it well-suited for observing the Moon, planets, and double stars. However, it has a narrow usable field of view and noticeable off-axis distortions. The primary is an ellipsoid, and the secondary paraboloid.

The Cassegrain telescope (f/4 - f/12), proposed by Mersenne and later Cassegrain, offers a long focal length in a compact tube. While its usable field is narrow and off-axis distortions are present, its high magnification excels for observing the Moon, planets, and double stars, and allows for more comfortable eyepieces. The short tube provides better balance and stability. The primary is a paraboloid and the secondary hyperboloid.

The Ritchey-Chrétien (RC) design (f/8 - f/10), based on Schwarzschild's ideas, eliminated spherical aberration and coma found in earlier reflectors. Modern RCs often have higher secondary magnification (smaller obstruction) and surfaces closer to a paraboloid. RCs produce perfectly round star images, ideal for astrophotography, and are common in very large telescopes. However, they exhibit significant astigmatism beyond a 0.7° field and have the most pronounced field curvature of any design, causing stars at the image edges to appear larger. Both primary and secondary are hyperboloids.

The Dall-Kirkham design (f/12 – f/20) uses easily manufactured and tested mirrors, lowering costs and easing collimation compared to Cassegrain or RC telescopes. However, it suffers from significant coma (2-6 times more than a classic Cassegrain) and a narrow field, making it poor for wide-field photography. Image quality worsens with higher secondary magnification. The primary is a prolate ellipsoid, and the secondary is spherical. The Pressman-Camichel design, with reversed mirror shapes, has even more coma, 4-12 times that of a classic Cassegrain [155].

5.1 Primary mirror design

The primary mirror collects and focuses incoming light, with its aperture (D) determining light-gathering power and its focal length (f) setting the image scale. Most modern reflectors use a parabolic mirror (or other shapes, see Fig. 6) to eliminate spherical aberration, ensuring a sharp focus for on-axis rays [50]. Materials like Pyrex or Zerodur are favored for their low thermal expansion, minimizing distortion from temperature changes. The mirror is coated with aluminum or silver via vacuum deposition to achieve high reflectivity (typically >90%) across visible wavelengths.

5.2 Secondary mirror and optical configuration

The secondary mirror in reflectors redirects light to the eyepiece or detector. In the Newtonian design, a flat diagonal mirror reflects light to the side of the tube [52]. The Cassegrain configuration uses a convex hyperbolic secondary to fold the light path back through a hole in the primary, extending the effective focal length within a compact tube. The Ritchey-Chrétien variant employs two hyperbolic mirrors to correct coma, enhancing off-axis image quality for wide-field observations [3]. These can be seen in Fig. 6. Generally, the secondary’s size and tilt are optimized to minimize obstruction while maintaining alignment with the primary mirror [5,6].

5.3 Tube assembly and mount

The tube supports the mirrors and shields them from stray light. Open truss designs, common in large reflectors, reduce weight and thermal gradients, while solid tubes suffice for smaller instruments. The mount, typically equatorial or alt-azimuth, ensures precise tracking of celestial objects. Computer-controlled alt-azimuth mounts with derotators are standard in modern observatories, compensating for field rotation.

5.4 Testing and alignment

Mirror figuring is tested using interferometry or the Foucault test to verify surface accuracy to within a fraction of a wavelength. Collimation, the alignment of optical elements, is critical and often achieved with laser or star tests [54]. For segmented mirrors, as in the Keck Telescope, active control systems adjust individual segments in real time.

5.5 Applications

Reflector telescopes dominate professional astronomy due to their scalability and versatility. Large reflectors, such as the 10-meter Keck Telescopes, enable observations of distant galaxies, quasars, and exoplanets, leveraging their superior light-gathering capacity. The Hubble Space Telescope, a Ritchey-Chrétien type reflector, has revolutionized cosmology with its deep-space imaging. In amateur astronomy, Newtonian reflectors are popular for their cost-effectiveness and performance in observing nebulae and star clusters [53]. Beyond astronomy, reflectors are used in optical testing, laser communication, and solar concentrators, where large apertures and precise focusing are advantageous [58]. Their adaptability is enhanced by innovations like adaptive optics, which correct atmospheric distortion for ground-based observatories [59].

Reflector telescopes exemplify the synergy of optical theory and engineering precision, offering unmatched capabilities for astronomical observation. From Newton’s initial design to modern segmented and adaptive systems, their evolution reflects advances in materials, manufacturing, and computational techniques. The design process, centered on crafting parabolic mirrors, optimizing optical layouts, and ensuring structural stability, underpins their success across diverse applications. While smaller refractors excel in planetary imaging, reflectors dominate large-scale research due to their freedom from chromatic aberration and ability to scale to massive apertures. Future developments may focus on lightweight mirrors and AI-driven alignment, further enhancing their potential.

5.6 Image quality in Newtonian reflecting telescope

The Newtonian telescope is among the simplest and most widely used reflecting designs, particularly favored by amateur astronomers. It is also the most frequently constructed telescope by hobbyists, effectively making it the benchmark for evaluating other telescope types.

This telescope design includes a paraboloidal (commonly misnamed as "parabolic") primary mirror and a flat secondary mirror, which redirects the focused light out of the tube for either visual observation or photography. Newtonians typically have focal ratios ranging from f/4 to f/12. Focal ratios below f/4 are impractical due to significant coma near the edges of the field, while ratios above f/12 result in telescopes that are excessively long. Telescopes with slower focal ratios (f/7 to f/12) are best for viewing the Moon and planets, while faster focal ratios (f/4 to f/6) are more suitable for deep-sky observations and astrophotography at the prime focus.

In smaller, slower Newtonian telescopes, a spherical mirror may be used instead of a paraboloidal one. Although most modern Newtonians use paraboloidal mirrors, beginners often start with spherical mirrors due to their ease of manufacture and price.

The diagonal mirror, which redirects the light path, causes a central obstruction in the primary mirror. While it must be large enough to cover the desired field of view, it should be kept as small as possible to minimize negative effects on image quality. For visual observation, a fully illuminated field of about 10 mm in diameter is sufficient. However, Newtonians intended for photographic use require a larger diagonal to fully light the image area. Ideally, a telescope designer aims to use the smallest possible secondary mirror, not only to minimize light loss but also to reduce image contrast degradation caused by diffraction. Discerning observers can notice a decline in image quality when the central obstruction is 20% of the aperture, and it is generally agreed that it should not exceed 30%. A secondary mirror that is too small is not practical. In addition to the risk of surface imperfections near the edge of the diagonal mirror, such a small mirror may fail to fully capture and reflect the entire light cone. In fast Newtonian telescopes, the secondary mirror needs to be positioned slightly closer to the primary mirror and farther from the focal point to ensure that the focal plane is evenly illuminated around the optical axis. As a general guideline, illumination at the corners of a photograph should not decrease by more than 30 to 40%. For visual observing, a fully illuminated field with a 10 mm diameter is typically adequate [3].

5.6.1 Newtonian telescope with spherical mirror

In a spherical (concave) mirror, light rays that travel near the optical axis (paraxial rays) converge at a specific point-paraxial focus (designated as F in Fig. 7). However, rays farther from the axis come to focus nearer to the mirror, resulting in spherical aberration. Figure 7 illustrates a series of axial spot diagrams taken at different focal planes for a 200 mm spherical mirror with an f/8 focal ratio. The sequence begins at the paraxial focus (0.0 mm), and the light blur is smallest at a point 0.6 mm inside this focus. The way the blur size and the concentration of light in the image center change (shown in Fig. 7) is a typical signature of spherical aberration. In slower Newtonian telescopes, parabolizing the mirror isn't always necessary if the spherical aberration blur remains smaller than the Airy disk [3].

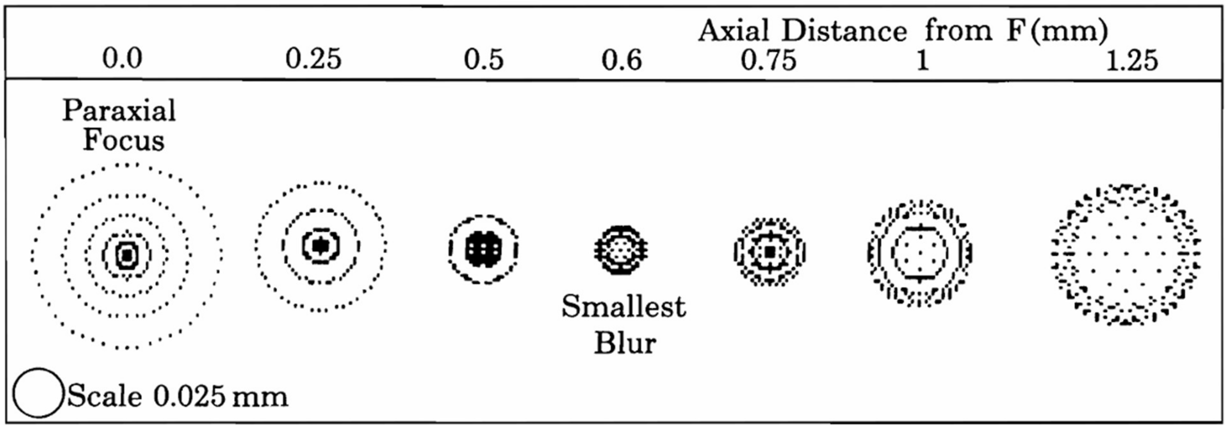


Fig. 7 Spot diagrams (at different focal planes) for a 200 mm f/8 spherical mirror [3]

In Fig. 8, the spot diagram sizes for various focal ratios with both the size of the corresponding Airy disks and the 0.025 mm photographic resolution limit are compared. For a 200 mm Newtonian telescope, a spherical mirror performs adequately for visual use at f/12 or slower (Fig. 8). For photographic purposes, mirrors used at f/8 or slower also do not require parabolizing.

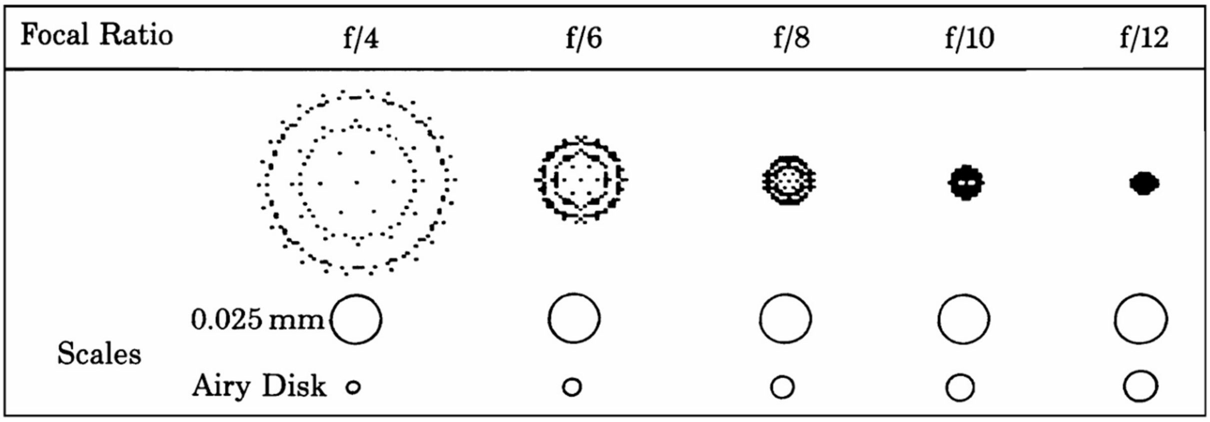


Fig. 8 Smallest blur spot diagrams for 200 mm spherical mirrors [3]

5.6.2 Newtonian telescope with paraboloidal mirror

Near the optical axis, spherical and paraboloidal mirrors share an identical radius of curvature. However, as you move farther from the axis, the spherical surface must be shaped slightly backward to ensure all rays converge at the same focal point (F), thereby correcting spherical aberration. This modified shape is a paraboloid. For mirrors with focal ratios of f/8 or slower, the difference between the edges of a spherical and a paraboloidal mirror is less than the wavelength of green light.

The primary optical defect in a Newtonian telescope is coma. Astigmatism also occurs, but typically only at wider image angles, and field curvature is another present but less significant aberration. When the entrance pupil is located at the mirror, which is usually the case, the optimal focal surface is positioned between the tangential and sagittal focal planes and curves inward with a radius equal to the telescope's focal length. Since coma greatly outweighs the other aberrations in Newtonian designs, using a curved photographic film or a field flattener offers minimal improvement.

Figure 9 presents spot diagrams for focal ratios ranging from f/4 to f/12, measured at off-axis distances of 0, 10, 20, and 30 mm on an optimally curved focal surface. At larger off-axis distances, particularly with fast primary mirrors, significant coma and astigmatism become apparent. Coma is the dominant aberration near the optical axis, while astigmatism appears farther out, identifiable by a secondary tail forming in the comatic blur pattern [3].

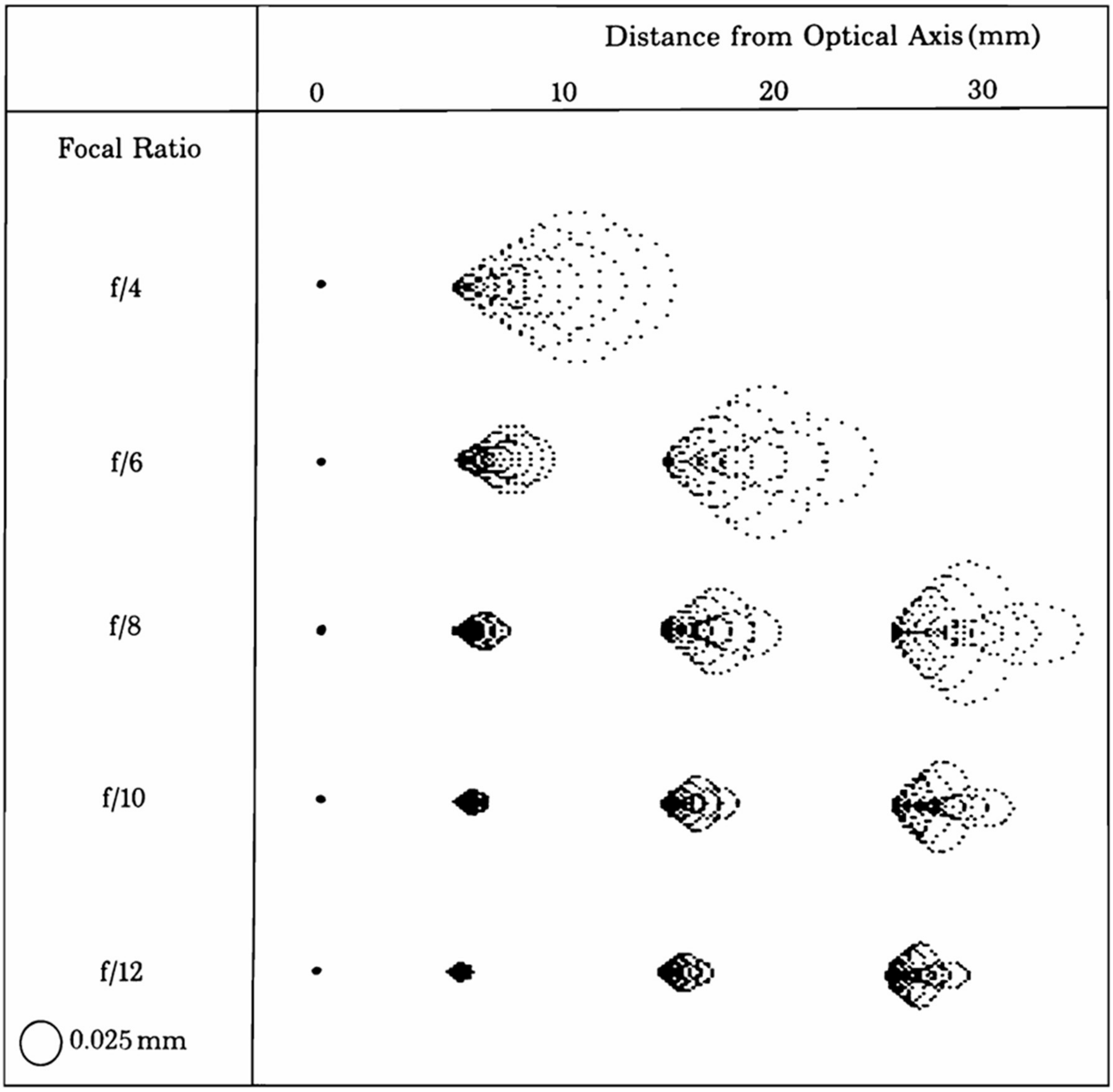


Fig. 9 Spot Diagrams for 200 mm paraboloidal mirrors [3]

Assessing the Newtonian telescope’s field that is usable for photography is challenging because photographic film or CCD/CMOS sensors may not capture the faint outer parts of the comatic blur. As a result, actual photographic images appear smaller than spot diagrams suggest. However, since some light is lost from the image center, the limiting magnitude is reduced. When high-quality photographic results are required, the 0.025 mm spot size criterion should be used. For less demanding applications, a blur of up to 0.100 mm at the edge of the film frame generally produces images that are acceptable to most astrophotographers.

Cassegrain telescopes often suffer from sky flooding, where stray light reaches the focal surface without mirror reflection, reducing contrast. Baffling is needed to block this stray light, but it increases central obstruction and may cause light loss at the field edges, especially in wide-field photography [3].

5.7 Image quality in the Cassegrain-type reflecting telescope

Cassegrain telescopes use a concave primary mirror and a small secondary mirror placed before the primary’s focus. Different designs vary by mirror shapes: Classical (paraboloid primary, hyperboloid secondary), Dall-Kirkham (prolate ellipsoid primary, spherical secondary), Ritchey-Chrétien (both hyperboloid), and Pressman-Camichel (spherical primary, oblate ellipsoid secondary). The secondary mirror reflects light toward the primary, forming an image behind it for easy observation or photography. The secondary also increases the system’s focal length but blocks some light, reducing brightness and contrast, so it’s kept as small as possible.

Ideal Cassegrain designs feature a short tube, small secondary, flat focal surface, and accessible focal plane, but achieving all simultaneously is impossible. Field curvature, caused by the secondary’s shape, is a key challenge and is more pronounced than in Newtonian or refractor telescopes. The field curves inward (concave to the sky). A flat focal surface requires equal radii of curvature of both mirrors, which conflicts with having a short tube and a small secondary.

High secondary magnification designs favor a short tube and small secondary but suffer from strong field curvature, which is fine for visual use but problematic for photography. Field curvature worsens as the secondary gets smaller and the mirrors get closer. Designers must balance between visual telescopes with small secondaries and strong curvature and photographic telescopes with larger secondaries and flatter fields. Field curvature can be corrected with curved film or field flatteners and mostly affects amateur scopes; professionals use additional optics or curved plates to compensate [3].

A Cassegrain telescope can be designed to eliminate spherical aberration, allowing for a sharp image at the optical axis, as long as the correct shapes are selected for both the primary and secondary mirrors. But the clarity of off-axis images is influenced by the shapes of these surfaces. The four key combinations of Cassegrain telescopes are presented in Table 3. Note that Schwarzschild constants (SC) are following: A sphere has an SC of 0 (indicating no deformation), prolate ellipsoid has an SC between -1 and 0, paraboloid has an SC equal to -1, hyperboloid has an SC less than -1, and an oblate ellipsoid has an SC greater than 0.

Table 3. Characteristics of four 200 mm f/8 Cassegrain telescopes (dimensions in mm) [3]

	Classical	**Ritchey-Chrétien**	**Dall-Kirkham**	**Pressmann-Camichel**
Focal ratio	8	8	8	8
Effective focal length	1600	1600	1600	1600
Secondary magnification	8/3	8/3	8/3	8/3
Primary radius of curvature	-1200	-1200	-1200	-1200
Primary Schwarzschild constant	-1	-1.13682	-0.61328	0
Secondary radius of curvature	-628.36	-628.36	-628.36	-628.36
Secondary Schwarzschild constant	-4.84	-6.55243	0	7.6755
Mirrors separation	-403.64	-403.64	-403.64	-403.64
Back focal length	523.64	523.64	523.64	523.64
1° field	27.9	27.9	27.9	27.9

Some opticians prefer the simpler spherical secondary of the Dall-Kirkham over the more complex hyperbolic secondary of the Classical Cassegrain. While easier to make, the Dall-Kirkham suffers from strong coma, limiting its field. The Pressmann-Camichel, with a spherical primary and heavily deformed secondary, also shows severe coma and supports only a narrow field. The Ritchey-Chrétien corrects coma and allows a wider field, but its highly aspheric mirrors are difficult to produce, making it favored only by professionals.

To compare these systems, spot diagrams (Fig. 10) were created for four designs with identical focal ratios but different surface shapes, as reported in [3]. Each had a 200 mm aperture, f/2.67 primary, and a focal surface 120 mm behind the primary. Diagrams show that Dall-Kirkham and Pressmann-Camichel are unsuitable for wide-field imaging due to coma. The Ritchey-Chrétien offers round star images, ideal for photography, but shows increasing astigmatism beyond 20 mm off-axis and has the strongest field curvature. The Classical Cassegrain matches Newtonian image quality but with more pronounced field curvature.

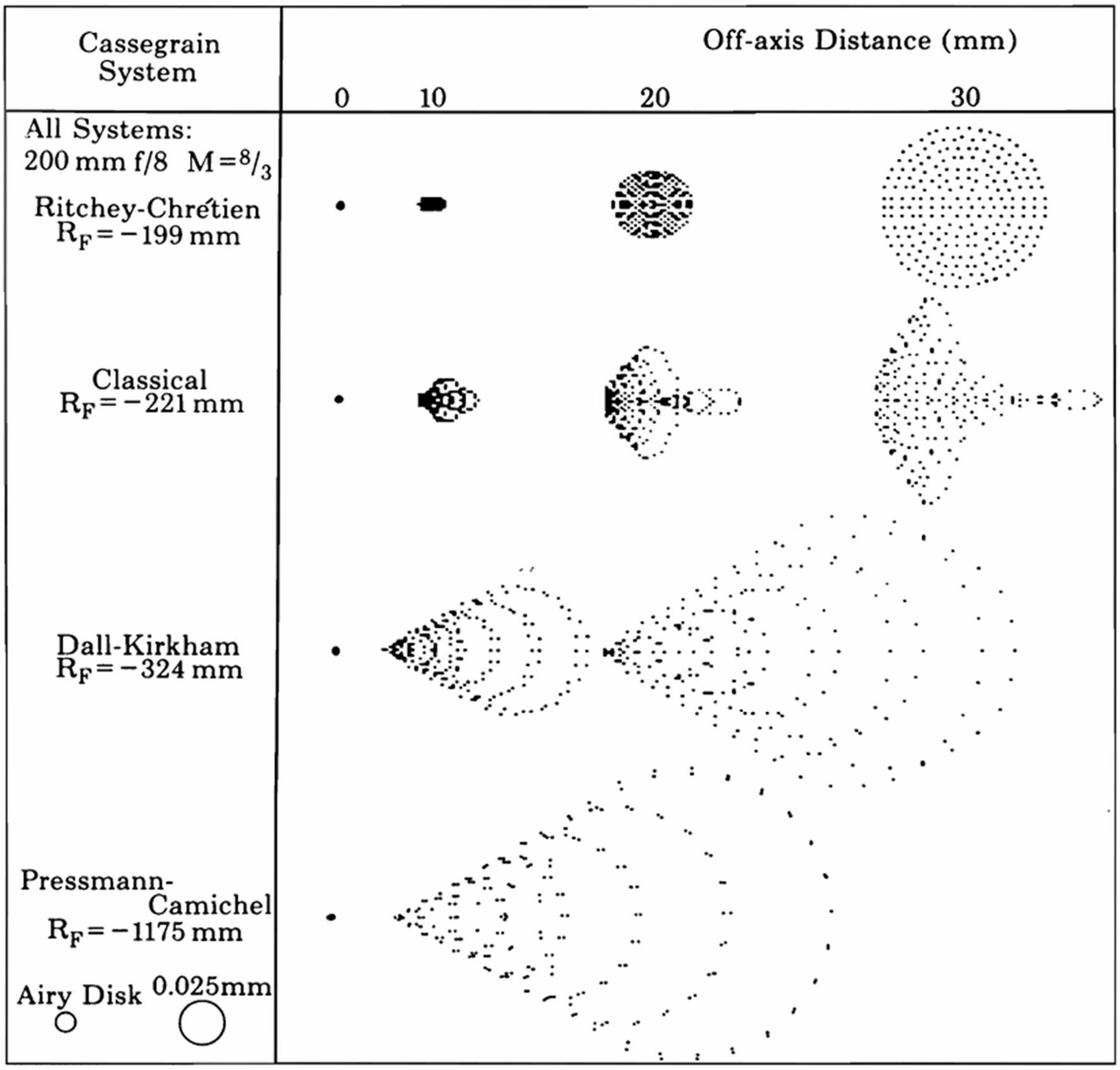


Fig. 10 Spot diagrams of four different types of 200 mm f/8 Cassegrain Telescopes [3]

6. Catadioptric telescopes

Catadioptric telescopes (Fig. 1) are sophisticated optical instruments that integrate both refractive elements (lenses) and reflective elements (mirrors) to form an image. This hybrid approach leverages the strengths of both refraction and reflection, enabling the correction of various optical aberrations such as spherical aberration, coma, and chromatic aberration. The result is an optical system that delivers high-quality images across a wide field of view.

The significance of catadioptric telescopes lies in their versatility and performance. By folding the optical path through the use of mirrors, these telescopes achieve a shorter physical length than refracting telescopes of equivalent aperture, making them highly portable - a critical advantage for amateur astronomers and field observers. Additionally, the incorporation of corrector lenses allows for larger apertures within a smaller package, enhancing light-gathering capability without significantly increasing size or weight.

Historically, the development of catadioptric telescopes began in the early 20th century. A pivotal advancement came in 1930 with Bernhard Schmidt's invention of the Schmidt camera, which utilized a spherical primary mirror and an aspheric corrector plate to achieve a wide, aberration-corrected field of view. Schmidt's design addressed spherical aberration effectively, though it required precise fabrication of the corrector plate [60].

Building on this foundation, Dimitry Maksutov introduced the Maksutov telescope in 1941 [61]. His design employed a thick meniscus corrector lens to correct spherical aberration in a spherical mirror system. The Maksutov telescope is renowned for its compact size and exceptional image quality, particularly suited for high-magnification tasks like planetary observation. Its simplicity and effectiveness have made it a staple in optical engineering.

The Schmidt-Cassegrain telescope (Fig. 11) presents a fusion of Schmidt's corrector plate with the Cassegrain reflector system, featuring a spherical primary mirror and a convex secondary mirror. This configuration folds the optical path, resulting in a compact telescope with a long focal length. The SCT balances field of view and image quality, making it a popular choice for visual observation and astrophotography.

Similarly, the Maksutov-Cassegrain (Fig. 11) adapts the Maksutov corrector lens to a Cassegrain layout, offering comparable compactness with slightly different optical characteristics. Its thicker corrector lens provides robust aberration correction, often yielding superior contrast for specific applications.

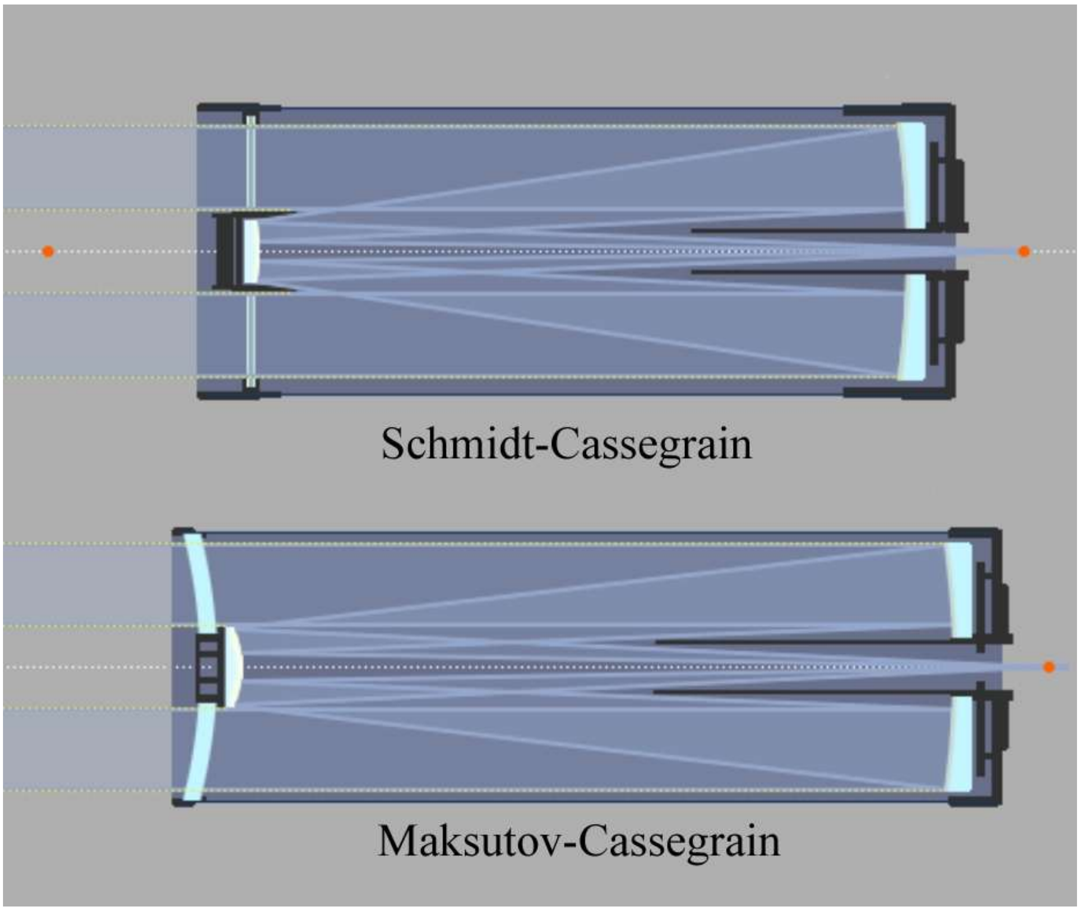


Fig. 11 Schmidt-Cassegrain and Maksutov-Cassegrain telescopes [155]

These instruments have become indispensable in astronomy and beyond, offering a balance of optical excellence and practicality. Despite their advantages, catadioptric telescopes are not without challenges. The additional optical surfaces introduced by corrector lenses can lead to light loss and internal reflections if not properly managed. Moreover, the manufacturing of precisely corrector elements can be complex and costly. However, technological advancements have largely mitigated these drawbacks, solidifying the catadioptric design’s place in modern optics.

Recent literature highlights advancements in catadioptric design. The integration of computer-aided design (CAD) and ray-tracing software has enabled precise optimization of optical elements [62]. Aspheric surfaces, once challenging to produce, are now more feasible thanks to modern manufacturing techniques [54]. Additionally, innovations in materials, such as advanced coatings and lightweight composites, have improved performance and durability [5,6].

Contemporary research also explores specialized catadioptric systems for space applications. For example, the Kepler space telescope utilized a Schmidt-based design to survey exoplanets, demonstrating the adaptability of catadioptric principles to the stringent requirements of space missions [63].

6.1 Methods of design

Designing a catadioptric telescope is a meticulous process that combines optical theory, computational tools, and practical engineering. The main goal is to create a system that meets specific performance criteria, such as aperture size, focal length, and field of view, while minimizing main aberrations and ensuring manufacturability.

6.1.1 Design process overview

The telescope design begins with defining the telescope’s specifications based on its intended use. For instance, an astronomical telescope might prioritize a larger aperture and longer focal length, while a terrestrial spotting scope may emphasize compactness and a wide field of view. Once these parameters are set, an appropriate catadioptric configuration is selected, such as a representative Schmidt-Cassegrain or Maksutov-Cassegrain (Fig. 11).

6.1.2 Schmidt-Cassegrain design

In the Schmidt-Cassegrain configuration (Fig. 11), the primary mirror is spherical, simplifying production compared to parabolic mirrors. A Schmidt corrector plate, placed at the telescope’s entrance, corrects for spherical aberration. This plate has an aspheric profile, carefully calculated to adjust the paths of incoming light rays so they converge accurately at the focal plane. The secondary mirror, typically convex, reflects light through a central hole in the primary mirror to the eyepiece or detector, folding the optical path and reducing the telescope’s length [3].

6.1.3 Maksutov-Cassegrain design

The Maksutov-Cassegrain (Fig. 11) employs a meniscus corrector lens instead of a plate. This thick, curved lens corrects spherical aberration while maintaining a compact design. The secondary mirror in a Maksutov-Cassegrain can be implemented in two ways: it can be a separate, precisely figured optical element mounted within the telescope tube, or it can be an aluminized spot directly applied to the central area of the rear surface of the meniscus corrector lens itself. This integrated secondary mirror offers the significant advantages of simplifying the alignment process [61].

6.2 Practical considerations

Beyond optics, the design must address mechanical stability, alignment ease, and manufacturing feasibility. The corrector plate or lens requires precise grinding and polishing to achieve its aspheric shape, a process that has been refined with modern CNC machinery [54]. Baffling is also critical to control stray light, as the folded optical path can introduce unwanted reflections if not properly shielded.

6.3 Testing and alignment

Once constructed, the telescope undergoes rigorous testing - often using interferometry or star tests - to verify performance. The alignment of optical elements is adjusted to minimize residual aberrations, ensuring the system meets its design goals.

6.4 Applications

Catadioptric telescopes serve a diverse array of purposes, capitalizing on their compact size, large apertures, and optical versatility.

In astronomy, catadioptric designs dominate the amateur market. Telescopes like the Celestron's Schmidt-Cassegrain series are prized for their portability and ability to observe a range of celestial targets, from planets to galaxies. Their folded design allows for large apertures (e.g., 8-14 inches) in a manageable size, ideal for transport to dark-sky sites. Professionally, Schmidt telescopes have been instrumental in wide-field surveys, such as the Palomar Observatory Sky Survey, mapping vast regions of the sky with high fidelity [5,6].

The Kepler Space Telescope stands as a prominent example of the successful application of catadioptric optical design in space-based astronomy. Launched by NASA in 2009, Kepler employed a modified Schmidt telescope configuration. This design provided a wide, flat field of view with minimal optical distortion, making it ideal for photometric observations. Kepler's mission was to detect exoplanets by continuously monitoring the brightness of over 150,000 stars within a fixed field of the Milky Way. Its optical system was specifically optimized to measure minute changes in stellar brightness caused by the transit method - a planet passing in front of its host star, causing a slight and periodic dimming. Thanks to this innovative catadioptric design, Kepler revolutionized the field of exoplanetary science, leading to the discovery of thousands of exoplanets, many of which are Earth-sized and located in the habitable zones of their stars [63].

For terrestrial use, catadioptric spotting scopes provide high magnification and clarity in a compact form. Birdwatchers and nature enthusiasts benefit from their portability, while surveillance and military applications leverage their long-range capabilities.

In scientific contexts, catadioptric systems appear in specialized equipment. Photolithography machines, used in semiconductor manufacturing, employ catadioptric projection optics to image intricate patterns onto wafers with sub-micron precision [62]. Similarly, laser beam expanders and optical alignment tools utilize catadioptric principles for their aberration-corrected performance.

With the advent of digital imaging, catadioptric telescopes paired with CCD cameras have become powerful tools for astrophotography. Their design supports the high resolution and light sensitivity required for capturing detailed images of celestial objects.

Looking forward, catadioptric telescopes are poised for further advancement. The integration of adaptive optics could enhance their performance for ground-based astronomy by compensating for atmospheric distortion. Innovations in materials, such as lightweight carbon fiber tubes and advanced coatings, promise greater portability and efficiency. Additionally, as digital imaging continues to evolve, catadioptric designs may be optimized further for astrophotography and automated sky surveys. Catadioptric telescopes represent a mature yet dynamic field, with a rich history and a promising future, continuing to push the boundaries of optical engineering.

6.6 Image quality in Schmidt-Cassegrain catadioptric telescope

The Schmidt-Cassegrain Telescope (SCT) is popular among amateur astronomers due to its compact design, portability, closed tube, and good color correction. Most commercial models have an f/10 focal ratio, but many users don't realize SCTs belong to a broad family of designs with various configurations. Despite having only three components, a primary mirror, a secondary mirror, and a Schmidt corrector, the SCT allows many design variations. These include different corrector placements, mirror shapes (spherical or aspheric), and focal positions (in front of or behind the primary). A key difference from the classical Cassegrain reflecting telescope is the Schmidt corrector, which removes axial spherical aberration (using a corrector plate), though off-axis aberrations like coma and astigmatism require specific designs to correct.

Practically, SCTs fall into two main categories: visual and photographic. Visual SCTs feature strongly curved focal surfaces and small secondary mirrors (<30% of the primary diameter), which makes them unsuitable for wide-field photography without additional correction. Photographic SCTs are designed for flat-field imaging, requiring nearly equal radii of curvature for both mirrors. This results in large secondary mirrors (45–60% of the primary diameter) and poor performance for visual use at high magnifications.

"Visual" Schmidt-Cassegrain telescopes feature a curved focal surface and a moderately sized secondary mirror, making them well-suited for visual observation. In this compact setup, the secondary mirror is attached to the inner surface of the Schmidt corrector lens. The primary mirror has an f/2 focal ratio, with a secondary magnification of 5, comparable to standard commercial 200 mm f/10 telescope systems.

Fig. 12 presents spot diagrams for a 200 mm f/10 Schmidt-Cassegrain with spherical mirrors (as reported in [3]), both on- and off-axis, for flat and curved focal surfaces. While axial sharpness is excellent, off-axis performance suffers from strong coma, comparable to a 200 mm f/5 Newtonian. This makes compact SCTs with spherical mirrors unsuitable for wide fields. To reduce coma while maintaining sharp axial images, designers may: (a) aspherize the primary, (b) aspherize the secondary, (c) aspherize both, or (d) reposition the Schmidt corrector (abandoning compactness). The most common solution is aspherizing the secondary; using both aspheric mirrors is rare in amateur telescopes.

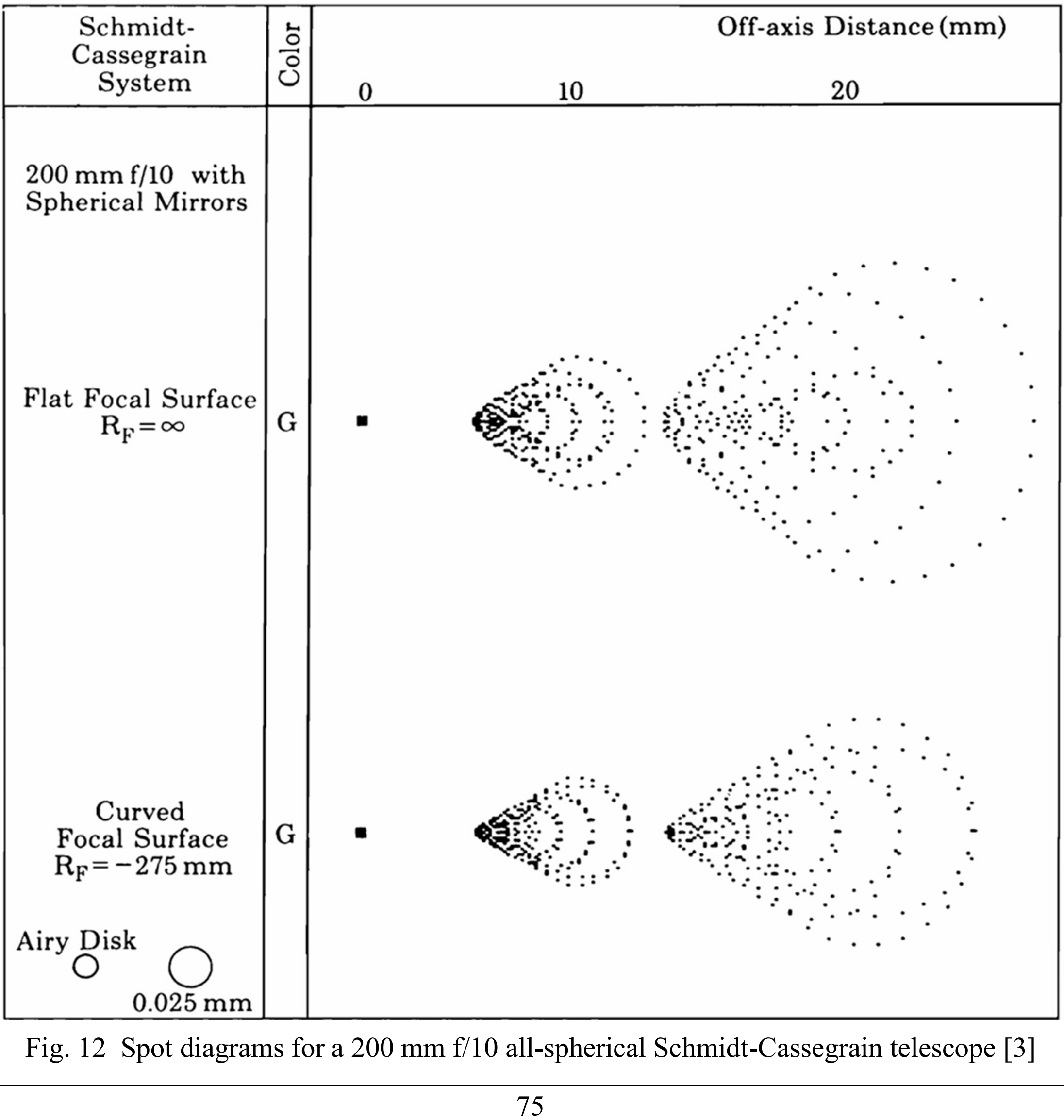


Fig. 12 Spot diagrams for a 200 mm f/10 all-spherical Schmidt-Cassegrain telescope [3]

Figure 13 shows spot diagrams for an optimized 200 mm f/10 Schmidt-Cassegrain with an aspherized secondary, as reported in [3]. At the flat focal surface (top row), sharp images are limited to the central 20 mm - about the size of the full moon - with increasing blur beyond that. At the curved focal surface (bottom row), image quality is diffraction-limited over a wide area, offering excellent visual performance. Photographic results can improve with curved film or a field flattener. In this design, the Schmidt corrector provides 83.42% of the spherical aberration correction, with the rest handled by the aspheric secondary [3].

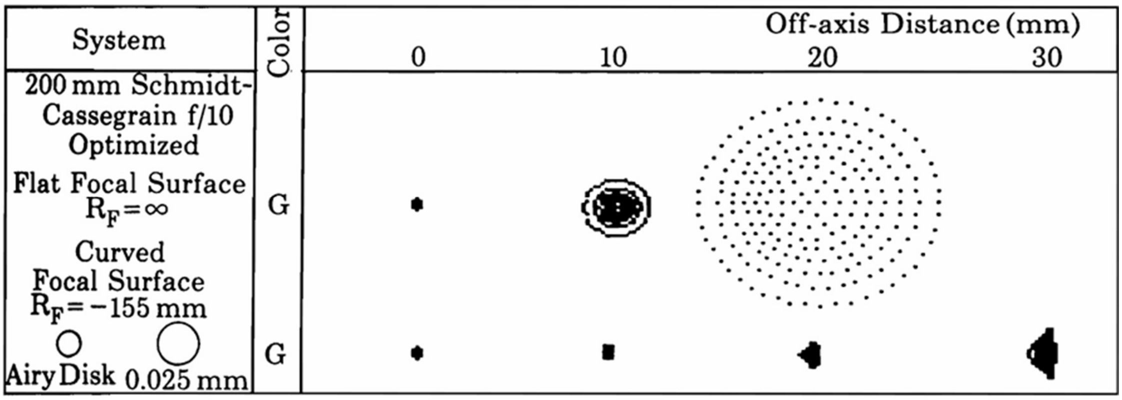


Fig. 13 Spot diagrams for an optimized (secondary mirror aspherized) 200 mm f/10 SCT [3]

Figure 14 shows spot diagrams for red, green, and blue light in the SCT system optimized for green, as reported in [3]. The remaining color error is due to spherochromatism - the change of spherical aberration with wavelength. All colors focus on the neutral zone where the corrective lens has no refractive power. Elsewhere, refraction varies by wavelength, causing color differences. In this system, color aberration is about five times less than in a comparable f/15 Fraunhofer doublet refractor of the same aperture. The main drawback of this design is the large central obstruction from the secondary mirror and its holder, which is 34% of the entrance pupil diameter, larger than ideal for observing low-contrast objects like planetary details. Reducing the secondary size by using a slower system (f/15 or f/20 instead of f/10) shrinks the field of view, making the telescope less versatile. Additionally, Cassegrain telescopes need baffle tubes to block stray light, which prevents reducing the central obstruction below about 30% in a 200 mm instrument [3].

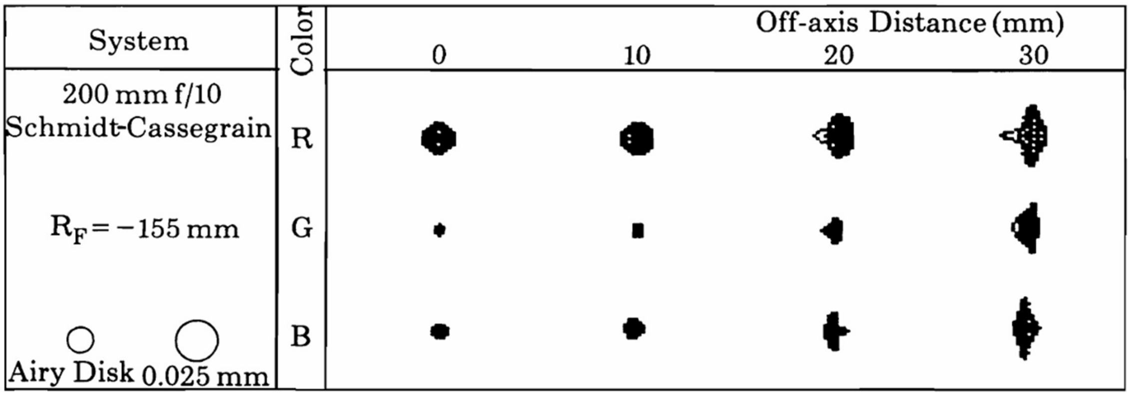


Fig. 14 Color correction for an optimized 200 mm f/10 SCT [3]

Comparing the off-axis performance of the optimized visual Schmidt-Cassegrain telescope to a similar f/10 two-mirror Classical Cassegrain reflector shows the latter has spot diagrams about four times larger. The SCT's better performance is due to two factors: moving the entrance pupil from the primary mirror to the Schmidt corrector and adding an extra optical surface, which allows better correction of aberrations across three surfaces instead of two [3].

Flat-field Schmidt-Cassegrain telescope design is also discussed in reference [3]. Table 4 provides paameters for this 200 mm f/4 telescope.

Table 4 Data for 200mm f/4 Schmidt-Cassegrain telescope (dimensions in millimeters) [3]

Corrector	
- Radius, first surface	flat
- Thickness	4
- Glass	517643
- Paraxial radius, second surface	-83250
- Radius of neutral zone	86.6% of 100 mm
- Relative power	50.5%
- Distance to primary	977.2
Primary	
- Radius of curvature	-845.6
- Distance to secondary	-231.6
Secondary	
- Radius of curvature	-809.7
- Distance to focal surface	358.285
Radius of focal surface	flat
Effective focal length	800
Geometric focal ratio	f/4
Diameters	
- Schmidt Corrector	216
- Stop	200
- Primary mirror	220
- Secondary mirror	110
Distance, stop to corrector	300
1° Field	14.0

This is essentially a variant of the Slevogt flat-field telescope design, where a compromise is achieved by positioning a 200 mm diameter stop 300 mm behind the corrector. This causes the primary mirror's diameter to be roughly the same as the corrector's. For visual use, a large obstruction reduces contrast by spreading light into diffraction rings, which is undesirable. However, in photography, a 55% central obstruction (present in this system) is acceptable since over 80% of the light remains concentrated in the Airy disk and first diffraction ring, well within photographic sharpness limits. Additionally, the large secondary mirror eliminates the need for baffling by blocking stray light due to its size and the long tube design [3].

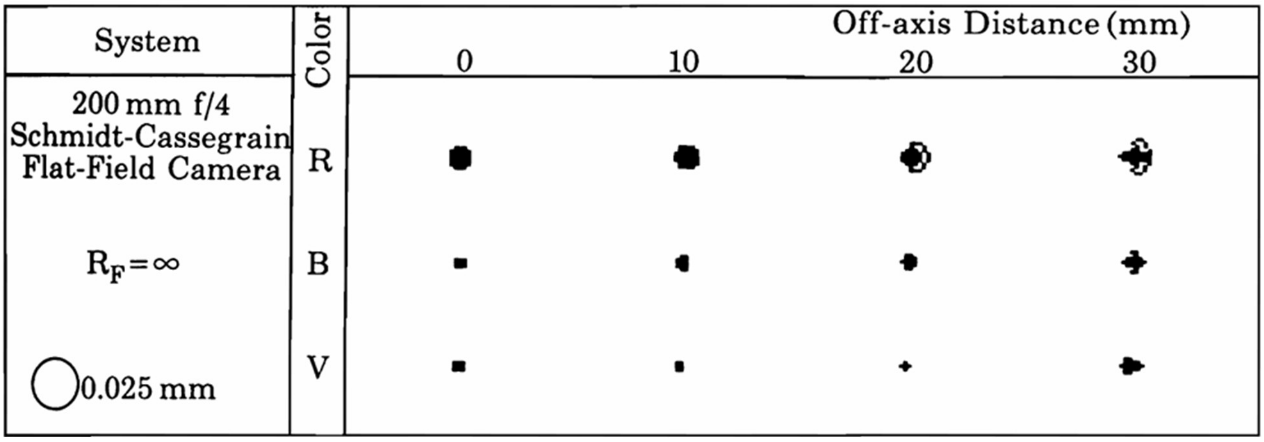


Fig. 15 Spot diagrams for a flat-field 200 mm f/4 Schmidt-Cassegrain telescope [3]

Fig. 15 shows spot diagrams for this flat-field 200 mm f/4 Schmidt-Cassegrain telescope. It can be seen that this design meets the 0.025 mm criterion over the entire 60 mm diameter flat field under consideration, and that lateral color is within the same limit as well.

6.7 Image quality in Maksutov-Cassegrain type catadioptric telescopes

John Gregory introduced the f/23 Gregory Maksutov-Cassegrain, a compact catadioptric telescope with spherical optics and an aluminized secondary spot on the meniscus corrector, making the design accessible to amateurs. His f/15 version improved color correction, requiring slight aspherization. Later adaptations refined the design for both visual use and astrophotography.

This section reviews several 200 mm aperture models and assesses their optical performance, as presented in reference [3]. In this regard, Fig. 16 presents six representative Maksutov systems, providing a basis to discuss degrees of freedom - the adjustable optical parameters like curvature, spacing, thickness, glass type, or aspheric surfaces. Effective image correction requires at least as many degrees of freedom as the aberrations being corrected.

The Gregory Maksutov-Cassegrain (Fig. 16) shows notable coma and astigmatism, as evident in the spot diagrams (Fig. 17). These aberrations can't be corrected in the mentioned design because the secondary mirror shares the curvature of the corrector’s back surface. Adding a degree of freedom, such as an independently curved secondary, is necessary for improvement. One solution, used by some manufacturers, involves grinding the corrector center differently, but this is complex for amateurs. A simpler method is the Rumak design (introduced by Harrie Rutten), which attaches a separate convex secondary. Also, an f/15 system, the Rumak offers better off-axis performance, improved color correction, and a flatter field (Fig. 17). Both systems perform near the diffraction limit on-axis in red, green, and blue light, but the Rumak clearly outperforms off-axis. The Gregory design also suffers from considerable spherochromatism. The Rumak design also has drawbacks: it requires a longer optical tube and a larger secondary mirror compared to the Gregory Maksutov. Designing a Rumak-type system with the same tube length as the Gregory is feasible, but it demands an additional degree of freedom. This can be achieved by aspherizing one of the optical surfaces - either the corrector, primary, or secondary mirror. However, producing aspheric surfaces is complex and typically impractical for most applications, making this solution less appealing [3].

Additional design flexibility can be achieved by adjusting the spacing between the corrector and secondary mirror, especially in fast Maksutov-Cassegrain systems (faster than f/8) with all-spherical surfaces. This approach is used in designs like the Simak and Sigler (Fig. 18). However, for systems faster than f/4, spherical surfaces alone lead to excessive aberrations. In the f/2.5 Companar, Klaas Compaan (Fig. 19) minimized chromatic aberration by adding a weak positive lens in front of the corrector. To correct residual spherical aberration, the lens was slightly aspherized - a step only necessary for systems faster than f/2.85 [3].

The characteristics (radius of curvature, axial thickness, medium type, focal length) of the six Maksutov systems are given in Table 5, while their spot diagrams are shown in Figs. 17, 18 and 19.

Among the Maksutov-Cassegrain telescopes reviewed, only the Companar features a flat focal surface, having been designed specifically for astrophotography. Other models are suitable for both photographic and visual use, where keeping the secondary mirror small is important to reduce central obstruction.

The Companar achieves its flat field by nearly matching the radii of curvature of the primary and secondary mirrors. However, this results in a large secondary mirror (60% of the aperture), causing a 36% light loss at the center and up to 35% at the edges. Despite this, the large obstruction has minimal effect on image sharpness due to the compact diffraction pattern at f/2.5.

Compared to traditional Maksutov cameras, flat-field designs like the Companar are more complex, requiring larger optics and in some cases, a spider to support the secondary mirror. However, the Companar avoids the need for a baffle thanks to its large secondary, which effectively blocks stray light.

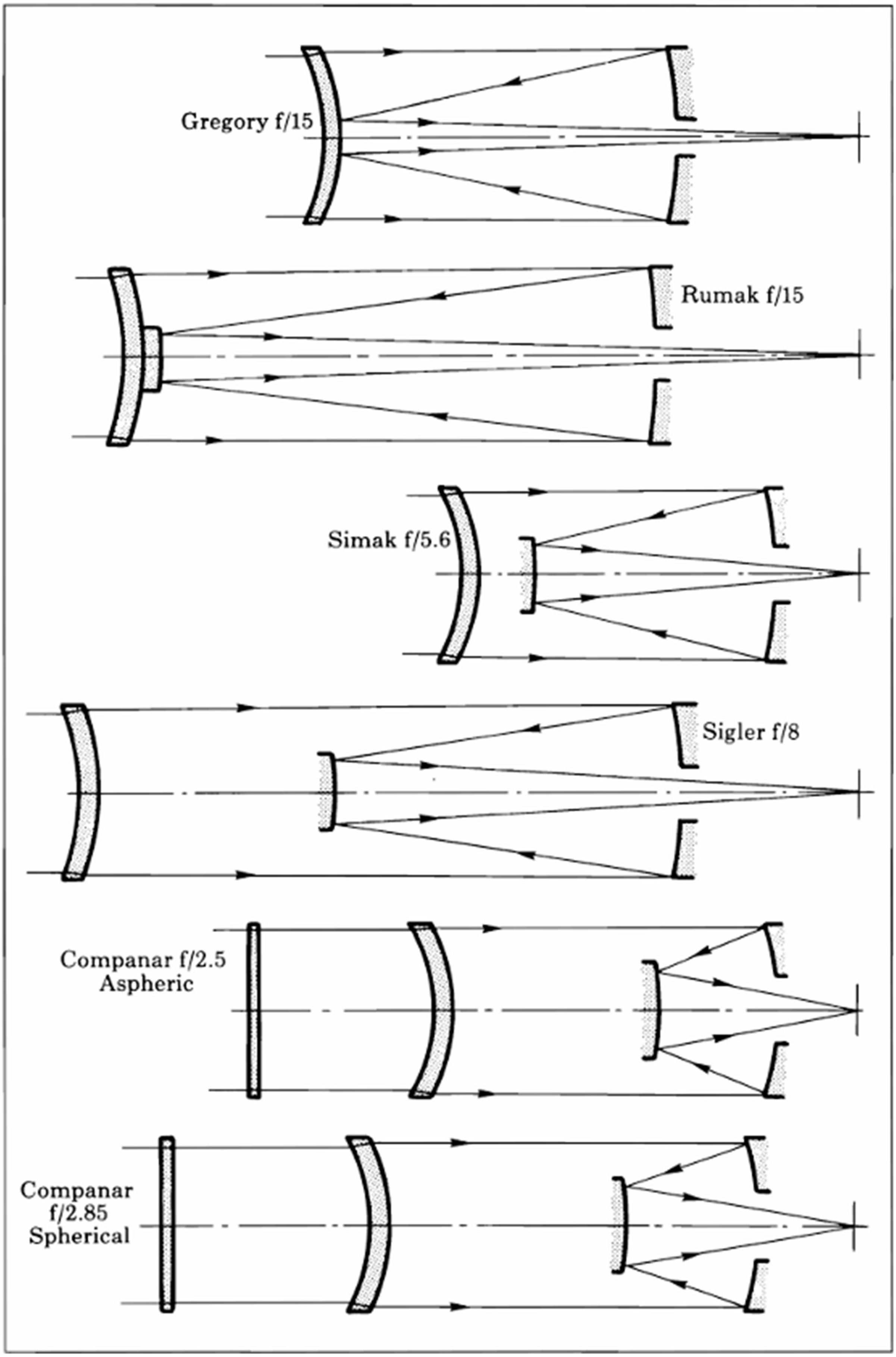


Fig. 16 Schemes of six Maksutov-Cassegrain telescope systems [3]

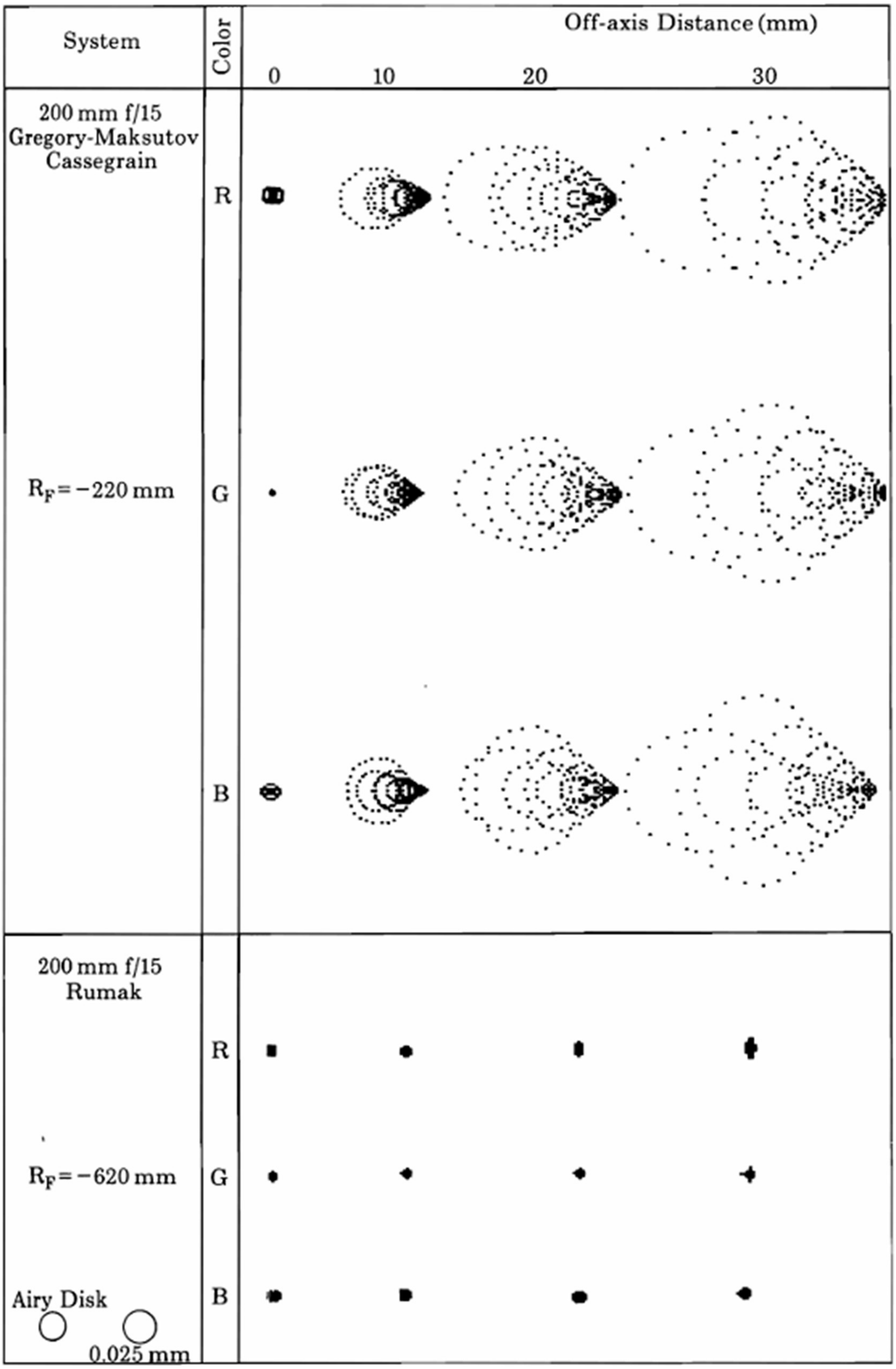


Fig. 17 Spot diagrams for the Gregory-Maksutov and Rumak telescopes [3]

When comparing Maksutov- and Schmidt-Cassegrain designs, the Maksutov generally requires larger elements due to the stronger outward bending of rays by its negative corrector lens. Both the aspheric Companar and the f/4 Schmidt-Cassegrain offer excellent image quality, but their construction is challenging, making them suitable only for highly skilled amateurs seeking top-tier, wide-field astrophotographic performance [3].

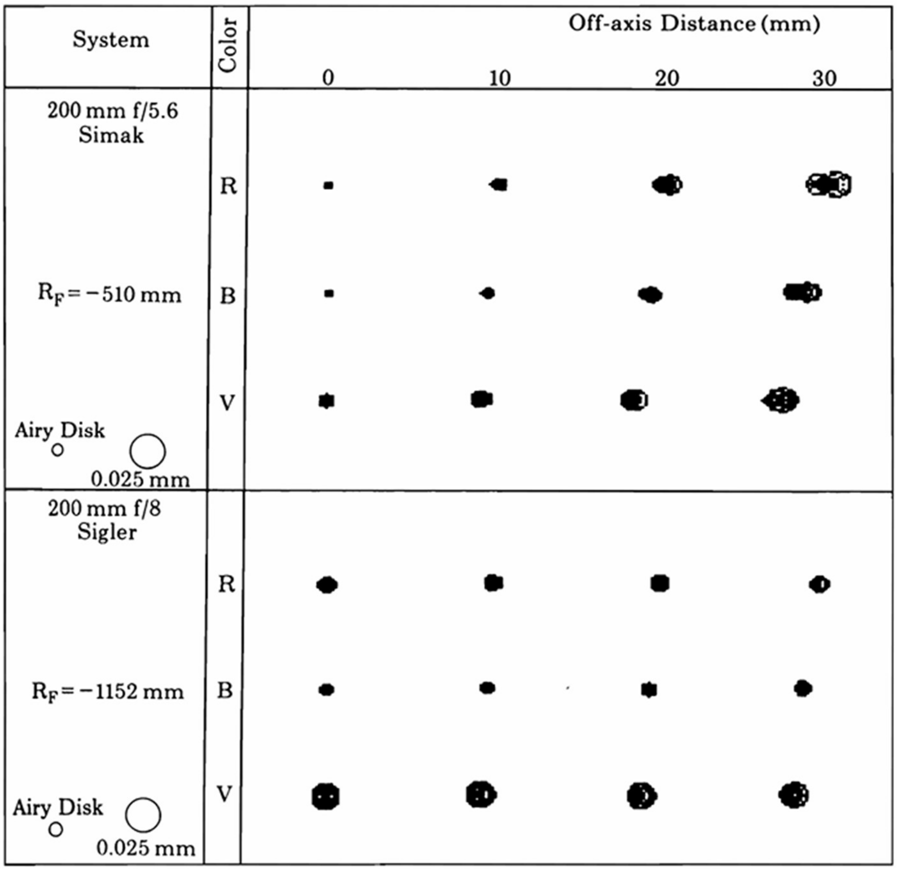


Fig. 18 Spot diagrams for the Simak and Sigler Maksutov systems [3]

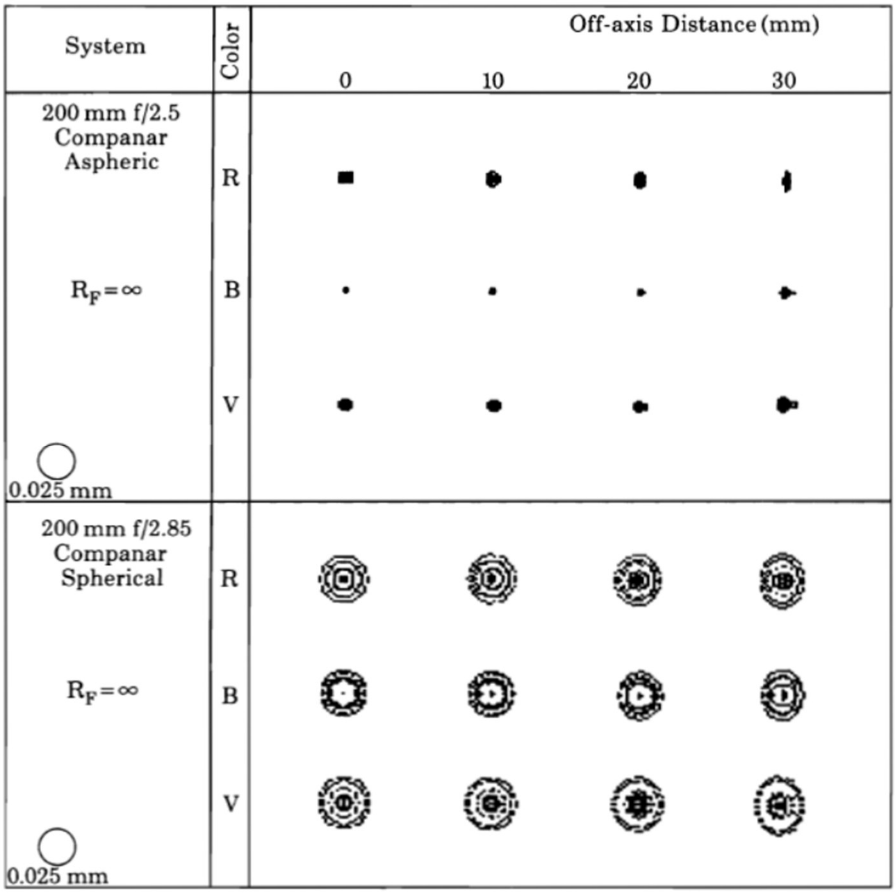


Fig. 19 Spot diagrams for the Comapanar systems [3]

Table 5. Three 200 mm Maksutov-Cassegrain systems (dimensions in millimeters) [3]

System	Gregory	Rumak	Simak	Sigler f/8.0	Companar (aspheric)	Companar (aspheric)
Focal Ratio	f/15	f/15	f/5.6	f/8	f/2.5	f/2.8
R_1 Radius of Curvature	-219.413	-334.956	-217.465	-297.709	11070	12300
T_1 Axial Distance	17.347	20	19.425	20.6	10.0	11.1
M_1 Medium	517642	517642	517642	517642	517642	517642
R_2	-229.6	-346.673	-229.025	-309.455	-11070	-12300
T_2	403.653	605.8	355.575	693.582	210.0	233.3
M_2	Air	Air	Air	Air	Air	Air
R_3	-980.453	-1592.2	-847.2	-1311.818	-210.0	-233.3
T_3	-403.653	-589.7	-289.675	-413.473	18	20.1
M_3	Air	Air	Air	Air	517643	517643
R_4	-229.6	-598.072	-451.75	-847.091	-228.0	-253.4
T_4	620.679	832.12	388.222	631.75	388.175	439.88
M_4	Air	Air	Air	Air	Air	Air
R_5					-520.84	-584.13
T_5					-140.0	-155.56
M_5					Air	Air
R_6					-500.68	-562.44
T_6					240.283	275.19
M_6					Air	Air
Effective Focal Length	3000	2964	1122	1595	504	572
1° Field	52.4	51.7	19.6	27.8	8.8	10.0

7. Conclusions

In summary, this review has explored the design characteristics and image quality aspects of the three main categories of amateur astronomical telescopes: refractors, reflectors, and catadioptric systems. Drawing on an extensive literature base of over 150 references, the analysis has addressed key optical features, strengths, and limitations of each design. Comparative evaluation has highlighted how these instruments differ in terms of optical performance, ease of use, portability, and maintenance, as well as their effectiveness in both visual observation and astrophotography.

Particular emphasis was placed on the management of aberrations, field curvature, and diffraction - elements central to achieving high image quality. Based on these findings, practical guidance is offered for users with different observational goals, whether focused on planetary detail, deep-sky imaging, or introductory stargazing. This synthesis of theory and application provides a useful framework for selecting the most suitable telescope type according to individual needs and interests. Below are given general conclusions that can be drawn.

Refractor Telescopes

Design: Uses lenses (typically a doublet or triplet objective).

Optical Characteristics:

- Excellent contrast and sharpness, especially for planetary and lunar observation.
- Prone to chromatic aberration unless apochromatic lenses are used (which are costly).
- High light throughput (no central obstruction).
- Low maintenance – sealed tube keeps optics clean and aligned.
- Heavy and long tubes for larger apertures; expensive in large sizes.

Reflector Telescopes – Newtonian type

Design: Uses a parabolic primary mirror and a flat secondary mirror.

Optical Characteristics:

- Very good image quality, no chromatic aberration.
- Coma off-axis in fast focal ratios.
- Slight contrast reduction due to central obstruction.
- Requires collimation; open tube prone to dust and thermal currents.
- Cost-effective; large apertures are affordable.

Reflector Telescopes – Cassegrain type

Design: Uses a concave primary and convex secondary mirror.

Optical Characteristics:

- High resolution; suitable for planetary and deep-sky imaging.
- Can have field curvature and coma; often corrected in compound variants.
- Larger central obstruction than Newtonians.
- Closed tube (when combined with corrector); mirrors need alignment.

Schmidt-Cassegrain Telescope (SCT)

Design: Combines spherical primary mirror, Schmidt corrector plate, and secondary mirror.

Optical Characteristics:

- Good all-around performance; minor spherical aberration corrected.
- Field curvature and coma; not ideal for wide-field astrophotography without a corrector.
- Moderate light throughput due to central obstruction and multiple reflections.
- Compact and lightweight for aperture size.
- Needs occasional collimation; the corrector plate helps seal the system.

Maksutov-Cassegrain Telescope (MCT)

Design: Uses a spherical primary mirror and meniscus corrector with a built-in secondary.

Optical Characteristics:

- Very sharp and high contrast; excellent for lunar and planetary observation.
- Very well corrected; minimal chromatic and spherical aberration.
- Slightly lower light throughput due to the thick corrector and central obstruction.
- Very compact; slower focal ratios (e.g., f/12–f/15).
- Rarely needs collimation; sealed system is low maintenance.
- Long cool-down time due to thick corrector; narrow field of view.

Below is given quick comparison table, based on previous conclusions.

Characteristic	**Refractor**	**Newtonian**	**Cassegrain**	**Schmidt-Cassegrain**	**Maksutov-Cassegrain**
Chromatic Aberration	Yes (unless APO)	None	None	None (minor SA)	Minimal
Contrast	Excellent	Good	Moderate	Good	Excellent
Field of View	Moderate	Wide	Narrow	Moderate	Narrow
Portability	Low - Moderate	Moderate	Moderate	High	High
Maintenance	Very low	High	Moderate	Low - Moderate	Very low
Astrophotography	Good (APO)	Very good (fast)	Good	Good (with corrector)	Fair (narrow field)

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