Issue 1

1.1 The Houghton Telescope: An Optimum Compromise?

By Harrie G. J. Rutten & Martin van Venrooij

A question often asked by amateur telescope makers is: "Which telescope is best?" Everybody who delves into this question will find out soon that each type of telescope has its own set of advantages and disadvantages. These disadvantages may, for instance, pertain to image quality, width of field, focal ratio, weight, etc. Consequently, it is impossible to get an unambiguous answer to the question, "Which telescope is best?".

The situation is more favorable for those who specialize in only one field; for instance, the observation of planets or deep-sky photography. For these tasks, specialized instruments are available with which optimum results can be achieved.

However, most amateurs want a universal instrument that can be used in different fields of observation and photography with a favorable combination of properties and only minimal disadvantages. This type of instrument may be called an "optimum compromise."

The authors have looked for such a compromise and the following discussion presents their findings.

1.1.1 Requirements for an Optimum Compromise

We believe that an instrument designed to meet the needs of most casual observers or astrophotographers could be achieved with an instrument possessing the following characteristics:

1. Compact design
2. Aperture 200–250 mm
3. Suitable for visual and photographic application
4. Minimum central obstruction (30–35% of the aperture at most)
5. High photographic speed, perhaps *f*/4.

The first requirement is, in our view, the most important. A compact telescope can be handled and transported easily and may also find a place in the car during vacation trips. The second demand is self-evident. A large aperture has many advantages. The third requirement is the most difficult to achieve, for three reasons:

1. The image sharpness should be good not only in the middle of the field, but at the edges as well. Unfortunately, most amateur telescopes do not provide good off-axis imagery.
2. The focal surface should be flat, or nearly so. This is another area in which most amateur instruments fall short.
3. For astrophotography, the instrument must have a large spectral range, providing a high degree of color correction from red to violet.

The fourth demand refers to the need to keep the central obstruction as small as possible. Large obstructions cause diminished performance on low contrast objects. The last requirement is necessary for deep-sky photography where a relatively wide field and short exposure times are desirable.

1.1.2 Possible Instruments

A check on the existing instruments reveals that most of them do not satisfy the above-mentioned criteria simultaneously.

- A refractor with a large aperture and short focal length will have strong chromatic aberration.
- A short-focus Newtonian suffers from coma which degrades off-axis image sharpness.
- A Cassegrain, when designed as a short-focus instrument with a flat field, has a large secondary mirror, which may approach 55% of the aperture! This is also the case with various catadioptric designs such as the Schmidt-Cassegrain and the Maksutov.

The solution can be found only in the group of catadioptric derivatives of the Newtonian telescope; i.e. systems with a single mirror combined with a corrector to suppress the off-axis aberrations.[1]

An example of an instrument which meets most of our prescribed criteria is the Rutten Newtonian with a small corrector lens just inside the focus. However, this is an *f*/15 lunar and planetary telescope and would not allow us to achieve our requirements for a "fast" wide-field instrument. The first instrument we will consider consists of a spherical mirror and a Schmidt corrector. This type of instrument is called a Schmidt-Newtonian and should not be confused with the Schmidt camera. In the latter the corrector is placed at twice the focal length, and the design is frequently referred to as a "concentric" system. Image quality in this system is exceptionally good. However, this instrument may only be used for photography since the focal plane lies inside the instrument.

In the Schmidt-Newtonian shown in Figure 1.1.1, the corrector is placed inside the focus of the mirror. While the image plane is accessible for visual use, this design lacks the performance of the Schmidt camera in that off-axis aberrations

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[1] Rutten, Harrie and Martin van Venrooij. "The Rutten Newtonian," *Telescope Making* 35, 1988/89, pp. 46-50.

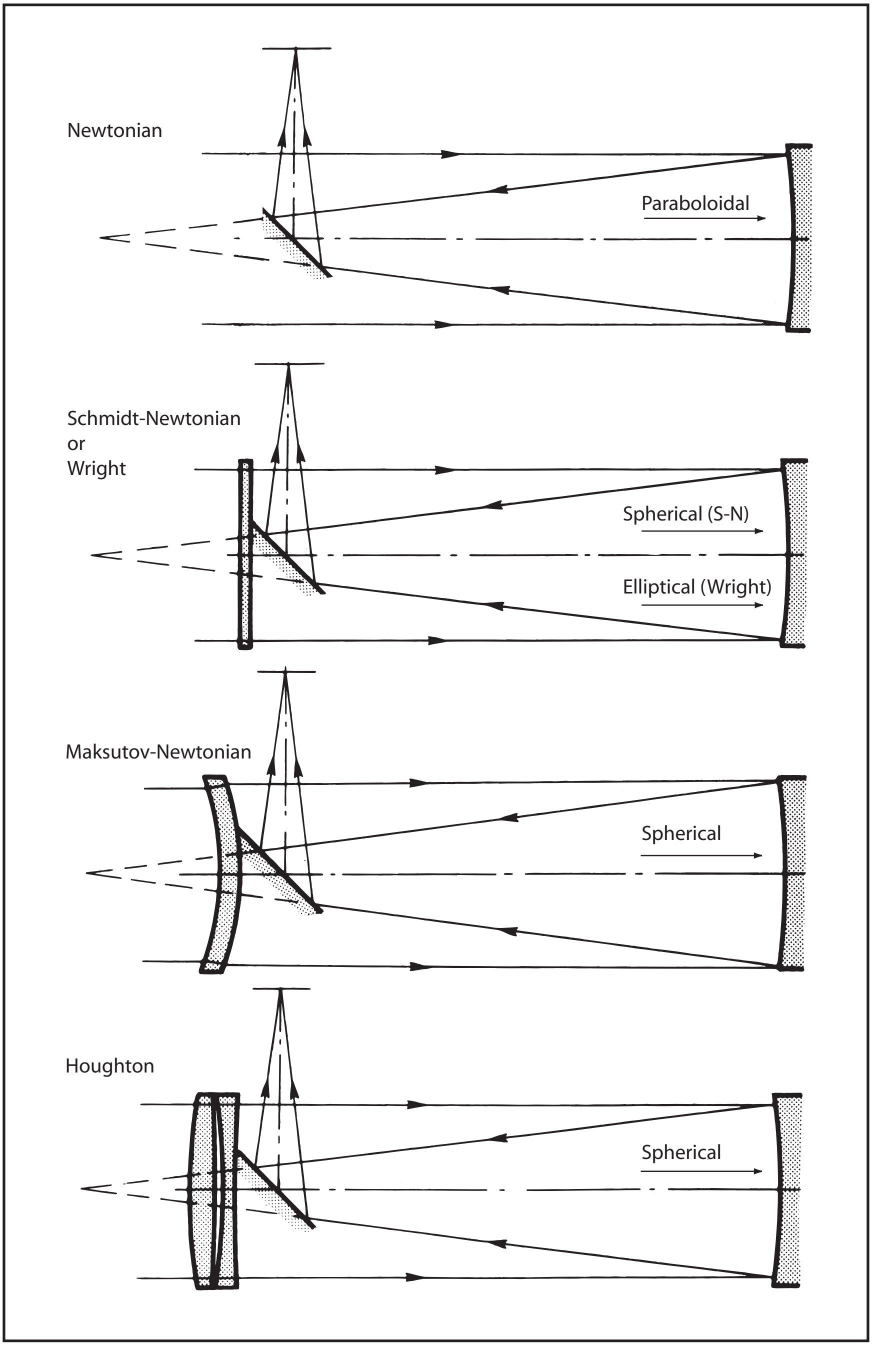

Fig. 1.1.1 *The Newtonian and some catadioptric derivations.*

such as coma and astigmatism are not fully corrected.

A better optical system is the Wright design, in which the mirror has been deformed into an ellipsoid. In this design, coma can be fully removed. However, this system still suffers from astigmatism and making an ellipsoidal mirror is not an easy task.

The next system uses a Maksutov corrector to remove the spherical aberration produced by the spherical primary mirror. The corrector is much closer to the mirror than in a Maksutov camera; therefore, coma cannot be completely corrected.

1.1.3 Enter the Houghton

The Houghton consists of a spherical primary mirror and a two-element corrector of zero optical power.

Thus, the corrector can remove spherical aberration without introducing the chromatic aberration normally associated with large doublet lenses. The particular two-lens design we analyzed was made by Lurie in 1979.[2] It is but one example of the various types of correctors Houghton proposed in 1944.[3]

Design methods for this type of instrument may be found in *Telescope Optics, Evaluation and Design*.[4]

1.1.4 Optical Performance

In Figure 1.1.2, we see the optical performances of four catadioptric systems compared to that of a Newtonian telescope. We show the images of a star on the best-fitting focal surface on the optical axis and at 10 mm and 20 mm from the axis. The last value corresponds approximately with the corner of a 24 x 36 mm negative. Compare the star images with the Airy disk for visual use of the telescope and a disk of 0.025 mm for photographic applications.

All instruments provide sharp images on-axis because spherical aberration has been completely eliminated. However, off-axis, the systems differ considerably. The Newtonian is not suitable for critical photographic applications because of its strong coma.

Coma is still present in the Schmidt-Newtonian (although to a lesser degree), and the Wright suffers from astigmatism. Note that while the Maksutov derivation is better than the Schmidt, only the Houghton is capable of rendering excellent image quality at the edge of the field of view.

Thanks to the long radius of curvature of the focal surface (nearly three meters!), we need no field flattener, and nearly all of the full image sharpness may be captured on a flat film plane.

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[2] Turco, Edward. “Gleanings for ATM’s—Making an Aplanatic 4-inch Telescope,” *Sky and Telescope*, Nov., 1979, page 473.

[3] Houghton, J. L. U.S. Patent 2,350,112. May 30, 1944.

[4] Rutten, H.G.J. and M.A.M. van Venrooij. *Telescope Optics, Evaluation and Design*. Richmond, VA: Willmann-Bell, Inc., 1988.

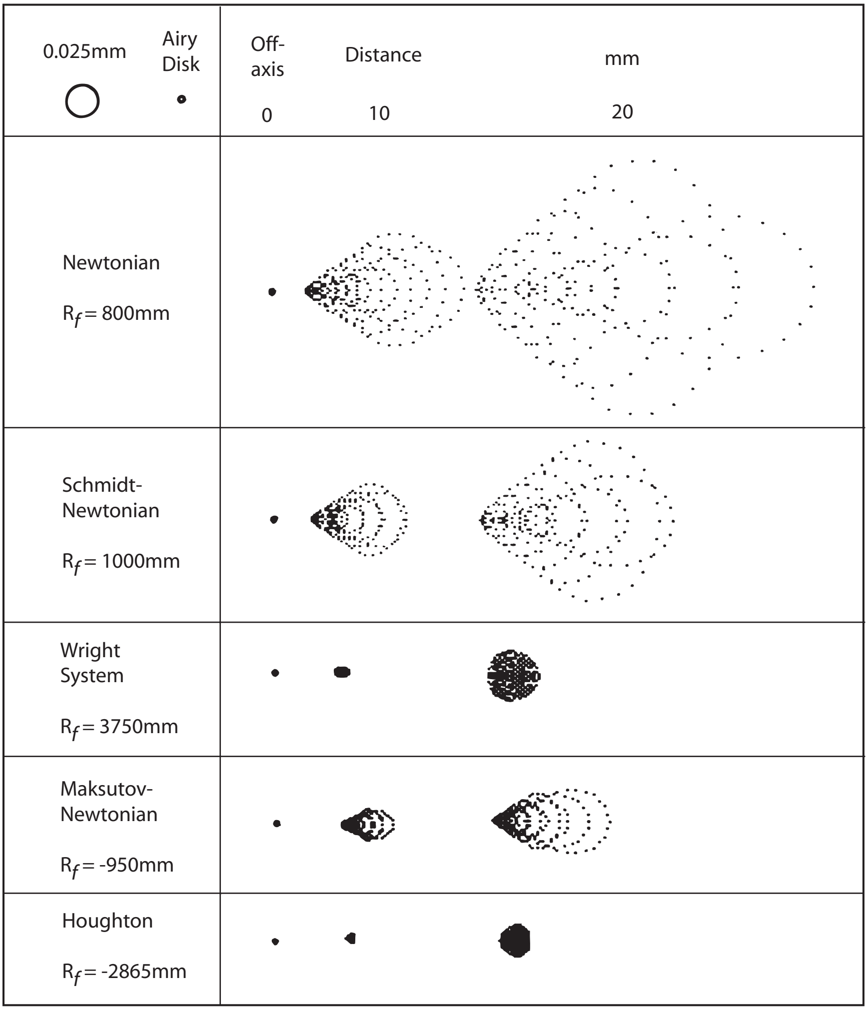

Fig. 1.1.2 *Spot diagrams for a 200 mm f/4 Newtonian and other catadioptric derivations.*

Furthermore, the color correction for the whole range from red to violet is excellent thanks to the fact that the corrector is a "zero power" element.

1.1.5 Diagonal Mirror Size

A disadvantage of the fast systems described is the presence of a rather large diagonal mirror. In order to receive all incoming parallel rays, the secondary mirror must create an obstruction no less than 29% of the full aperture. For off-axis bundles the size must be enlarged; and for the full illumination of a 24 x 36 mm negative, the size of the mirror (minor axis on a 200 mm instrument) would be approximately 46% of the aperture.

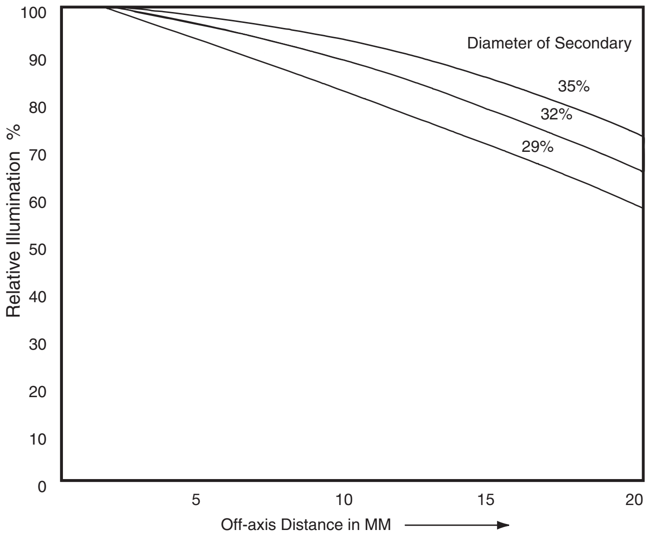

Fig. 1.1.3 *Relative illumination for instruments with secondary mirrors of various sizes.*

Table 1.1.1 Construction of a 200 mm $f/4$ Houghton telescope (data in mm)

Radii of curvature:	Glass Type:	Thicknesses:
R1 = 1286.81	Bk7	D1 =16
R2 = –4810.34		D2 =3
R3 = −1286.81	Bk7	D3 =12
R4 = 4810.34		D4 =617.67
R5 = −1590.97		D5 =–793.84

The distance from the primary mirror to the center of the diagonal is 575 mm and the diagonal mirror has a minor axis of 64 mm.

This figure is much too large to allow the instrument to be considered good for visual work. However, photographic applications often allow a light drop-off at the edge of the field of view approaching 40%.

This would indicate that one could use a secondary considerably smaller than the 46% obstruction just mentioned. Figure 1.1.3 shows the off-axis illumination relative to the center of the field for diagonals having a minor axis of 29%, 32% and 35% of the aperture for a 200 mm telescope.

We find the mirror with a 32% obstruction acceptable and tolerate a light reduction of 34% at the edge of the field.

Table 1.1.1 gives design data for the 200 mm instrument derived from Footnote 2.

1.1.6 Conclusion

The authors believe that the Houghton telescope is very close to a universal telescope for the demanding amateur. The advantage of the Houghton may be described as follows:

- Compact design
- Closed system
- Good image quality
- Fast system, suitable for visual and photographic application
- All surfaces may be left spherical
- Common glass types may be used
- No spider since the diagonal is attached to the corrector
- Relatively simple to construct
- Radii of curvature in complementing pairs allow the lenses to be ground and tested against each other.

Because of these favorable properties, it is surprising that this type of instrument is rarely built by amateurs, and that it is not offered commercially. The authors hope that this article will contribute to a broader knowledge of this fine instrument among amateurs.

1.2 The World of Unobstructed Reflecting Telescopes

By José Sasián

The quest for the best images in amateur astronomy has stimulated the development of unobstructed reflecting telescopes. These telescopes have evolved as a way to obtain high contrast images from instruments that are relatively inexpensive and easy to fabricate.

The central obstruction in conventional reflecting telescopes like the Newtonian reduces image contrast, and the supporting spider introduces diffraction artifacts. Such effects are clearly visible in many of the photos of stars and planets published in *Sky & Telescope* and *Astronomy* magazines. These problems can be avoided with optical designs employing tilted mirrors, which permit the light path to remain unobstructed. The story of the modern unobstructed reflecting telescope starts in Germany, where Anton Kutter popularized the Schiefspiegler. His writings about this “oblique” telescope include articles, a book, and *Sky & Telescope Bulletin A*. He labored for twenty-five years to bring diffraction-limited reflecting optics within the means of the ATM.

Thanks to the efforts of the late Robert (Bob) Cox, the Schiefspiegler was introduced in the United States. Shortly thereafter, telescope makers like Oscar Knab and Al Woods began work on such instruments. Early on, Bob made a Schiefspiegler for himself and encouraged Richard Buchroeder, an optical engineer with strong ATM roots, to examine other configurations of the tilted component telescope—or TCT. Buchroeder analyzed and designed several unobstructed models, and his work culminated in the classic *Technical Report 68* and his well-known Tri-Schiefspiegler. In the meantime, Arthur Leonard was also working on "giving the astronomical mirror its theoretical definition" and designed and demonstrated the Yolo. Leonard contributed to developing the theory of TCTs and designed other telescope configurations of interest like the Solano.

Strongly influenced by Richard Buchroeder's *Technical Report 68*, I further developed the theories associated with unobstructed telescopes that Buchroeder had initiated at the University of Arizona. Combining optical shop experience and an understanding of the theory of unobstructed optics, I was able to refine the Yolo and design and make the unobstructed Newtonian. In this article, I present a glimpse of how unobstructed reflectors are designed and discuss some of the best-known telescopes. Two unobstructed designs that may be of interest to ATMs are presented as well.

1.2.1 Telescope Design

The optical design of an unobstructed reflecting telescope involves the layout of a mirror configuration, aberration correction, and an overall evaluation of the design. The aberration correction drives the design process because there is usually not enough design freedom to obtain a good image quality and a practical telescope configuration. Thus, image quality is usually achieved at the expense of telescope simplicity and practicality.

The Main Aberrations

The field of view of a telescope is the angular extent of the object or scene it can image. At the focal plane, the field of view is represented by the diameter of the image. Every point in the object emits a wavefront, or a bundle of light rays, that will, if our design is good, form a corresponding image point at the focal plane. To have a perfect image, these wavefronts must converge to a true image point. In practice, due to the inherent geometry of telescopes and to mirror fabrication errors, the wavefronts are deformed, and the rays do not converge to a single point. Instead they form a "spot" or "blur" pattern as illustrated by the familiar spot diagrams. The compilation of all these spots of light forms the telescope image.

Image defects caused by the geometry of telescopes are called aberrations. Those that have the greatest impact on image quality are spherical aberration, coma, and astigmatism. The wavefront deformation and through-focus spot diagrams corresponding to these aberrations are illustrated in Figure 1.2.1.

Aberrations are measured from the vertex to the highest point of the deformation; this distance is measured along the direction of light propagation and is usually expressed in wavelengths. When the amount of aberration is small (about ⅒ wavelength of light) the image is essentially perfect within the limits imposed by the phenomenon of light diffraction. When the amount of aberration is about ¼ wavelength, the image is acceptable; and when there are several waves of aberration, the image is poor.

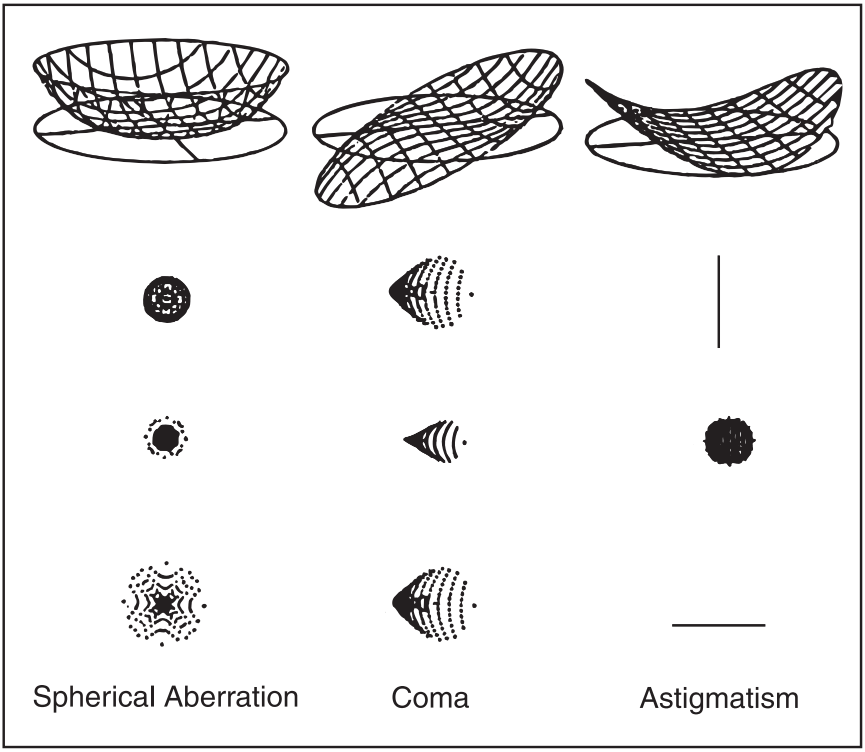

Fig. 1.2.1 *Wavefront aberrations and through-focus spot diagrams for spherical aberration, coma, and astigmatism Courtesy of R. Shack.*

In part, the task of the telescope designer is to correct or minimize the image aberrations. This is mainly done by causing the aberrations of one mirror to cancel the aberrations of the other, or by aspherizing one or more surfaces. If a mirror is polished with an asphericity similar to the wavefront deformation for spherical aberration, coma, or astigmatism, one can induce or correct such aberrations.

The design of unobstructed telescopes appears to be an obscure matter. This is because when the axial symmetry, typical in traditional telescope design, is broken by tilting the mirrors, the behavior of image aberrations becomes less simple.

The Newtonian and Cassegrainian designs can have only one aberration at the center of the field of view—spherical aberration due to their inherent axial symmetry. At off-axis field points, coma and astigmatism are generated. Coma mainly limits the extent of the usable field of view, and it grows linearly with the distance off-axis. For small fields astigmatism is usually negligible, and it varies with the square of the distance off-axis.

In contrast, in a tilted component telescope spherical aberration, coma, and astigmatism can all be present at the same time at the center of the field of view. The absence of axial symmetry around the field center results in this behavior. At off-axis field points, anamorphic distortion, coma and astigmatism (both varying linearly with the distance off-axis) and image plane tilt are the aberrations that affect the image.

Design Process

On one hand, the design of a known telescope configuration is simple because it is already understood. The design task becomes the adjustment of the various parameters to suit the particular requirements. Once in a while articles are published describing this process. For example, in *TM* #1, Buchroeder illustrates how to design Cassegrainian systems; Anton Kutter, in *Sky & Telescope Bulletin A*, describes the design of Schiefspieglers; and in *TM* #37, I describe how to design a Yolo telescope.

On the other hand, in the process of designing a new telescope, a novel mirror arrangement is proposed. The primary mirror, usually the largest one, is tilted so as to place the secondary outside the incoming light beam. The position of the secondary, its radius of curvature, and its tilt are chosen to yield a configuration physically possible and practical, and to correct aberrations. If more than two mirrors are involved, they are also used to accomplish such functions. The main concern in the design is to correct or minimize astigmatism, coma, and spherical aberration on-axis and linear astigmatism off-axis.

With designs employing only a few mirrors, there are not too many variables to correct for all the aberrations and obtain a practical telescope. Therefore, when the main aberrations have been corrected or minimized, then the image aberrations, the image anamorphism, image plane tilt, and the practicality of the configuration are evaluated. If these characteristics are acceptable, the main phase of the design process is completed. Other phases include checking mirror sizes and shapes, the design of testing configurations for the mirrors, tolerancing and light baffling.

Most amateur unobstructed telescopes have been designed with algebraic formulas to calculate the focal length *f*/ratio, and aberrations. Ray-tracing software has been only used to verify a theoretical prediction and optimize it. This design process implies a good understanding of telescope requirements—the “how?” and “why?” of previous designs and of optical design principles.

While the emphasis in designing and making unobstructed telescopes is here put toward obtaining a diffraction-limited image, there is no reason why these telescopes could not be designed with other goals in mind.

Design Considerations

The number of mirrors involved and their sizes are important considerations. The optimum number of surfaces is two since use of only one mirror leads to an uncomfortable viewing position, and three are too many—two can do the job. In addition, the light lost due to reflection is reduced when fewer mirrors are used. It is desirable to have small secondaries and tertiaries to reduce the telescope’s volume and weight, and increase its portability.

The roughness of mirror surfaces may also scatter light that reduces the im-

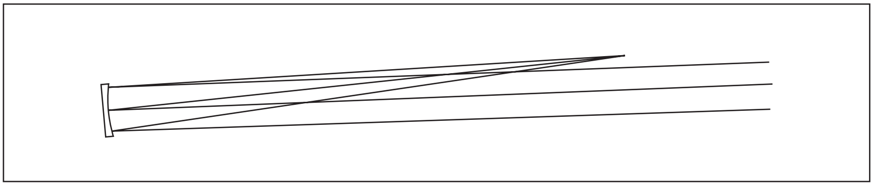

Fig. 1.2.2 *The Herschelian single-mirror telescope.*

age contrast. Aside from the atmospheric effects, the light scattered by rough or dirty surfaces is the limiting factor to obtaining perfect images in well-corrected unobstructed telescopes. In theory, and for the same amount of roughness, light scattering by mirrors is 16 times stronger than for refracting surfaces and about ½ as much as for a Mangin mirror surface. These facts indicate that the comparatively small amount of light scattered inherent in refracting telescope designs can be compromised if additional reflections are introduced to achieve comfortable viewing positions.

1.2.2 Telescope Designs

The following telescopes exhibit the best-known designs involving only mirrors and further illustrate how the design process is carried out.

One-Mirror Telescopes

A. The Herschelian

Figure 1.2.2. It is generally accepted that Herschel used this construction in his “front view telescope” to avoid the loss of light (about 33%) that a secondary mirror of speculum metal would have caused. This design was suggested by Lemaire in 1732 and tried by Herschel in his 20-foot telescope. Herschel seems to have been more concerned about light-gathering power than about optical quality. However, his decision to make a 40-foot front view telescope could have also been influenced by the simpler configuration. The mirror tilt in his instruments introduced about 20 waves of coma and 20 waves of astigmatism. It is surprising that, with this amount of aberration, he could observe details in the rings of Saturn along with certain spots and belts on the planets surface, as he reported in *Philosophical Transactions* articles between 1790 and 1806.

Tilting a concave spherical mirror introduces mainly coma and astigmatism over the field of view. The amount of these aberrations depends on the tilt angle, and therefore in any single-mirror telescope this effect is minimized. Spherical aberration can also be present; but if the focal ratio of the mirror is large enough (*f*/10 or greater), it becomes negligible. In order to minimize coma and astigmatism to a fraction of a wavelength, the *f*/number has to be increased to about 24 for the case of a 4-inch mirror. This results in a long and vibration-prone tube.

The astigmatism at the center of the field in a tilted spherical mirror can be corrected by making a double curvature surface. However, coma still dominates,

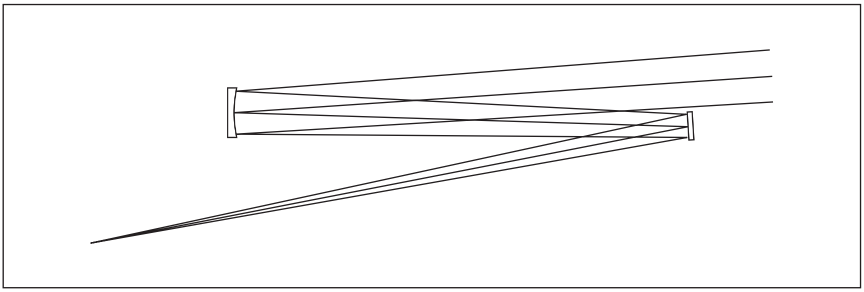

Fig. 1.2.3 *Anton Kutter's Schiefspiegler.*

and little speed is gained in trying to reduce the tube length or in improving image quality.

An off-axis paraboloid mirror is free of astigmatism, coma, and spherical aberration at the field center and could be used as an objective. Unfortunately the manufacture of this mirror is not an easy project for the amateur. Making a full paraboloid and cutting an off-axis section is not an attractive solution either.

The single mirror objective has the great advantage of simplicity, but it leads to an inconvenient viewing position, a long telescope tube, possible degradation of the incoming light beam by heat from the observer's head, and lower image quality due to aberrations. In spite of these facts, some amateurs still make unobstructed telescopes with a tilted, long-focus spherical mirror.

Two-Mirror Telescopes

A. The Schiefspiegler

The first-high performance unobstructed reflecting telescope was probably Anton Kutter's Schiefspiegler or oblique telescope[5] as it is illustrated in Figure 1.2.3. This design uses two spherical mirrors; the primary is concave and the secondary, convex. In this design astigmatism is corrected by making the aberration of one mirror cancel that of the other by the proper choice of secondary mirror tilt. The main residual aberration is coma, and it is minimized to ¼-wavelength by reducing the overall telescope speed to *f*/26 for a 4-inch primary.

A feature of Kutter design is that both mirrors have the same but opposite radius of curvature. This makes it possible to use the primary grinding tool for the secondary, and to test the convex surface by light interference against the concave mirror, which itself can be easily tested using the Foucault or Ronchi tests. However, additional work is required to polish the back surface of the secondary and in preparing the interference test.

B. The Yolo

Another unusual telescope design is Arthur Leonard's Yolo, named after a Cali-

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[5] Kutter, A. *Der Schiefspiegler*. Biberach and der Riss, 1953.

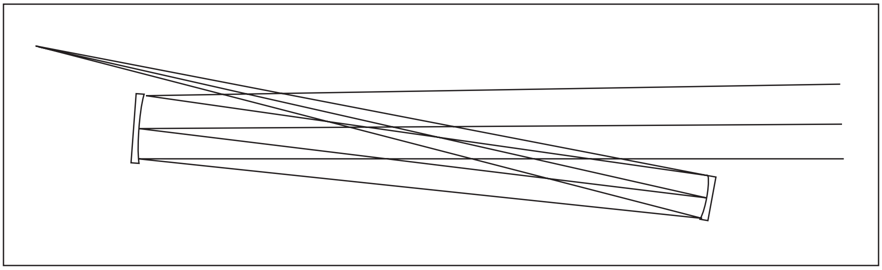

Fig. 1.2.4 *Arthur Leonard's Yolo.*

fornia county dear to the inventor. In this configuration he introduces a "warping harness"[6], and employs two shallow concave mirrors as shown in Figure 1.2.4.

This design corrects three aberrations at the center of the field: spherical aberration, astigmatism, and coma. Spherical aberration is corrected by hyperbolizing the primary, coma by the choice of the secondary mirror tilt, and astigmatism by mechanically deforming the secondary to induce a double curvature. The off-axis aberrations are minimized by increasing the focal length. This degree of correction enables the Yolo to have a faster speed and a larger aperture than is possible with a number of other TCTs. For example, Leonard has designed a 12.5-inch system operating at *f*/15.

One disadvantage of this configuration is that the secondary mirror size typically ranges from ⅔ to ¾ that of the primary. In designing Yolos, Leonard recommended minimizing the mirror tilt angles.

José Sasián introduced a refinement of the Leonard design in his article, "A Practical Yolo Telescope"[7]. This instrument features no warping harness and has better aberration correction. This design not only corrects spherical aberration, on-axis astigmatism, and on-axis coma; but linear astigmatism and linear coma as well. The key is to use the secondary mirror tilt to correct linear astigmatism and to further aspherize both mirrors. This refinement makes the Yolo "aplanatic" and provides a full degree of diffraction-limited performance for a 5-inch aperture working at *f*/8.6. The penalty for this performance is the difficulty of making the special aspheric secondary mirror. The secondary asphericity includes the three types of wavefront deformation discussed above.

The making of the secondary mirror for this aplanatic design showed that it is easy to make very smooth double-curvature surfaces with the degree of precision needed. The fact that double-curvature surfaces are easy to produce is of importance in telescope making because these surfaces allow one to correct both astigmatism and image anamorphism, thereby making feasible configurations that otherwise could not be pursued.

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[6] See example in Allan Mackintosh's *Advanced Telescope Making Techniques*, Willmann-Bell, 1986.

[7] Sasián, José M. "Gleanings for ATM's—A Practical Yolo Telescope," *Sky & Telescope.* August 1988, p. 198.

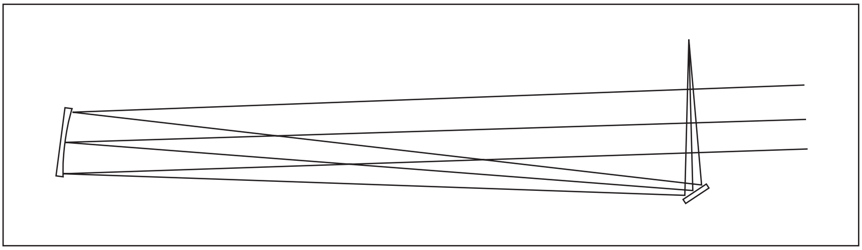

Fig. 1.2.5 *José Sasián's unobstructed Newtonian.*

C. The Unobstructed Newtonian

An example of the design flexibility that is gained by using double curvature surfaces is the unobstructed Newtonian illustrated in Figure 1.2.5.[8] This design pairs a standard long focus paraboloid primary mirror with a very strong double curvature secondary. The radius of curvature in one principal meridian of the secondary is twice as long as in the other principal meridian. This asphericity is used to correct the astigmatism contributed by both mirrors. In spite of the large secondary angle, coma, linear astigmatism, and image plane tilt can be minimized to obtain diffraction-limited images around the field center. This design has the usual advantages of the Newtonian—a comfortable viewing position at most elevations (even without an extra reflection), and the potential for satisfactory use with even a simple mounting. In addition the secondary can be made oversized to avoid a possible turned-down edge, and can be left circular.

Three-Mirror Telescopes

A. The Tri-Schiefspiegler

The image quality of the Schiefspiegler is limited when spherical surfaces are used, and the original Yolo required an undesirable warping harness. To solve the problem of obtaining a well-corrected image at the center of the field of view without a special aspheric or warping harness, Richard Buchroeder designed and demonstrated a three-mirror telescope that has been named Tri-Schiefspiegler,[9] see Figure 1.2.6. Like the Schiefspiegler, his design requires the primary and secondary mirrors to have the same, but opposite, radii of curvature and the tertiary to be a very long-radius concave mirror. The primary is a standard ellipsoid to correct spherical aberration, the secondary mirror mainly corrects coma, and the tertiary corrects astigmatism. These latter two are spherical and are ½ and ⅓ the size of the primary, respectively. The design has the advantage of being compact; a 12.5-inch unobstructed aperture working at *f*/20 can be assembled in a tube less

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[8] Sasián, José M. "Gleanings for ATM's—An Unobstructed Newtonian Telescope," *Sky & Telescope.* March 1991, p. 320.

[9] Buchroeder, Richard A. "Gleanings for ATM's—A New Three-Mirror Off-Axis Amateur Telescope," *Sky & Telescope.* December 1969, p. 418.

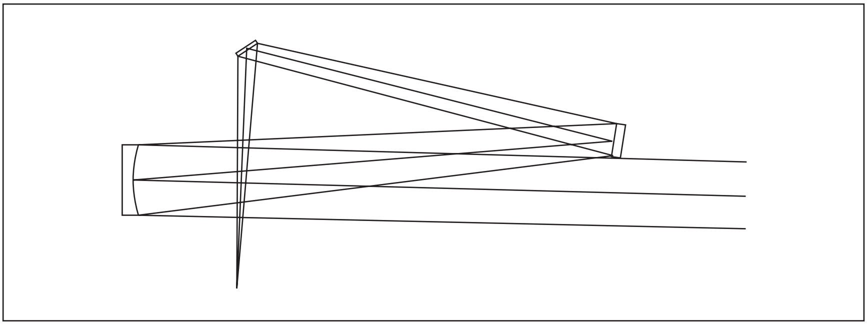

Fig. 1.2.6 *Richard Buchroeder's Tri-Schiefspiegler.*

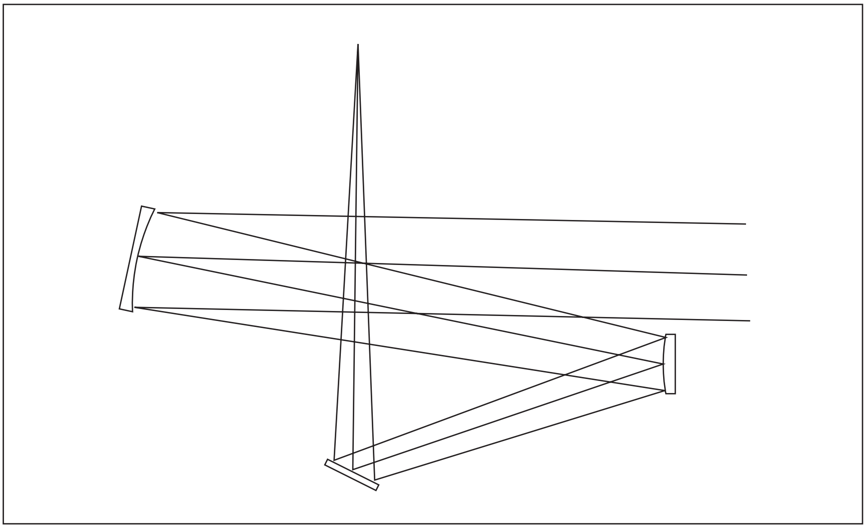

Fig. 1.2.7 *Kutter's Tri-Schiefspiegler.*

than 90 inches long. Makers of Buchroeder's design often praise the superb images that it provides.

Kutter's Tri-Schiefspiegler,[10] Figure 1.2.7, and Art Leonard's Solano,[11] Figure 1.2.8 are other examples of three-mirror telescopes corrected at the center of the field of view. As in Buchroeder's design, these require spherical surfaces for the secondary and tertiary mirrors, and under- or over-correction of the primary to control spherical aberration. They, too, have advantages and disadvantages.

B. Corrected Paraboloid

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[10] Kutter, Anton. "Gleanings for ATM's—A New Three-Mirror Unobstructed Reflector," *Sky & Telescope.* January 1975, p. 46.

[11] Mackintosh, Allan. *Advanced Telescope Making Techniques.* Richmond, VA: Willmann-Bell, Inc.

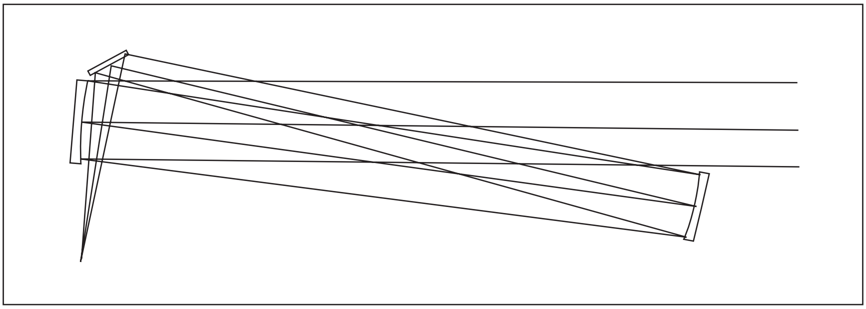

Fig. 1.2.8 *Leonard's Solano.*

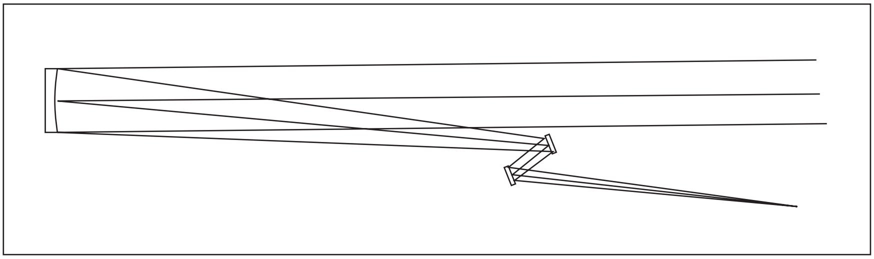

Fig. 1.2.9 *Design 1: 150 mm f/13.75 front-view Tri-Schiefspiegler.*

Although the use of double-curvature surfaces allows one to conceive well-corrected two-mirror telescopes, the design of three mirror instruments using only spherical surfaces continues to be of interest. The Tri-Schiefspieglers discussed above clearly illustrate that with three mirrors one can correct astigmatism and coma at the center of the field. However, a question that arises is: can linear astigmatism also be corrected? Please recall that this aberration is the one that most often limits the useful field of view, once on-axis astigmatism and coma are corrected.

The answer to that question is affirmative; Figure 1.2.9 illustrates such a three-mirror configuration, and Table 1.2.1 gives its specifications. This design solution was found by solving algebraic equations to account for astigmatism and coma at the field center and for linear astigmatism. A computer optimization was necessary to fine-tune the design that is limited by more subtle aberrations. A 150 mm aperture working at *f*/13.75 provides a diffraction-limited image over a ½° field of view. A problem with this configuration is that the image position is inconvenient, as in the Herschelian telescope. Thus, even though the aberration correction is successful, the practicality of the design is not high unless a fourth, plane mirror is used to reflect the image to a more favorable position.

1.2.3 Future Designs

It may be of interest to have a glimpse of future telescope concepts, such as that illustrated in Figure 1.2.10, for which the specifications are given in Table 1.2.2.

Table 1.2.1

Design 1: Tilted paraboloid corrected with spherical mirrors (150 mm aperture, *f*/13.75).

Primary	paraboloid
Radius	3000 mm concave
Conic constant	$K = -1$
Tilt angle	3°
Spacing	1000 mm
Secondary	spherical
Radius	829.6276 mm convex
Tilt angle	23°
Spacing	100 mm
Tertiary	spherical
Radius	1115.498 mm concave
Tilt angle	25°
Spacing	712.96 mm
Image plane tilt 6°	
Image anamorphism 2.3%	

Table 1.2.2

Design 2: Tri-Schiefspiegler with double-curvature tertiary (500 mm aperture, *f*/12.5).

Primary	ellipsoid
Radius	10353.26 mm concave
Conic constant	$K = -0.55$ ($K = -1.92$ aplanatic)
Tilt angle	5°
Spacing	2438.859 mm
Secondary	spherical
Radius	10353.26 mm convex
Conic constant	$K = 0$ ($K = -17$ aplanatic)
Tilt angle	15.5°
Spacing	2438.859 mm
Tertiary	double-curvature, concave
Radius	8238.783 mm (plane of symmetry) and 8967.392 mm
Tilt angle	10°
Spacing	1888.527 mm
Image plane tilt 0.0°	
Image anamorphism 3.1%	

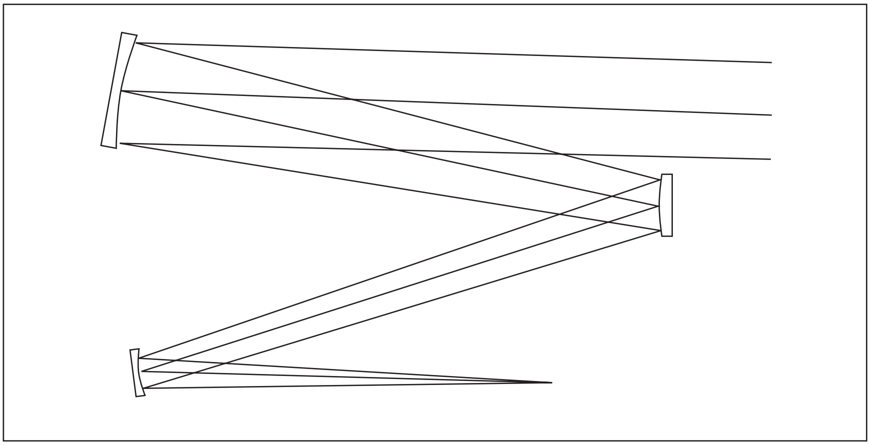

Fig. 1.2.10 *Design 2: 500 mm f/12.5 Tri-Schiefspiegler.*

This design uses an elliptical primary, a spherical secondary and a double curvature tertiary. It has been corrected for spherical aberration, coma, astigmatism, linear astigmatism, and image plane tilt. The aperture is 500 mm and the focal ratio

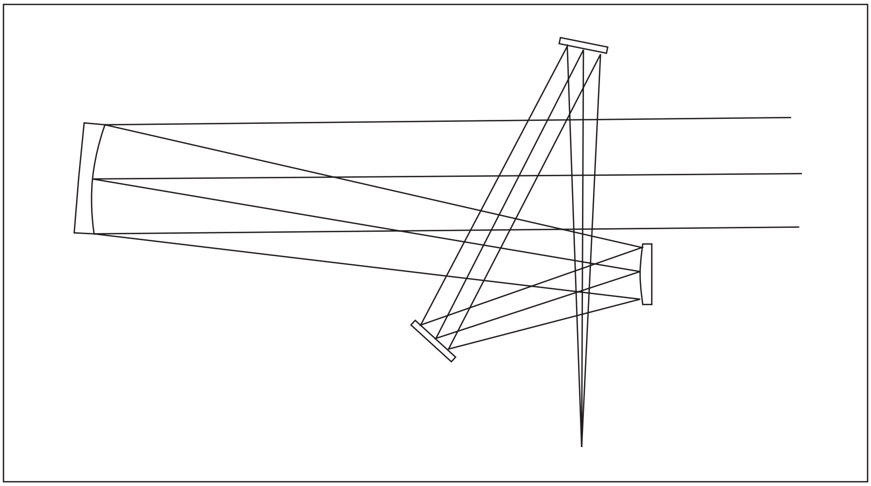

Fig. 1.2.11 *Folded version of the 500 mm Tri-Schiefspiegler.*

is 12.5. The performance of this design is limited by linear coma that can be corrected by hyperbolizing the primary and secondary mirrors. With this further correction, the design can compete with the Ritchey-Chrétien system and provide very good images over almost a one-degree field of view. The design goal was to obtain compactness in a large aperture; the distance between primary and secondary mirrors is 2439 mm for a 500 mm aperture. If the system is scaled down to a 250 mm aperture, a 150 mm secondary and a 100 mm tertiary mirror would be required. The design can be folded as illustrated in Figure 1.2.11, and the double-curvature tertiary can be null tested.

1.2.4 Conclusion

The design and fabrication of unobstructed reflectors is a very exciting part of telescope making, and there is a sufficient variety of unobstructed models to cover a large span of configurations and apertures. The known designs cover very well the span of small (3 to 5 inches) and medium apertures (6 to 8 inches) with great practicality and transportability. However, for larger apertures (10 inches or more), there is a need for very compact and moderately fast designs (*f*/8 to *f*/15). These designs will probably require three mirrors and a double-curvature surface like the large Tri-Schiefspiegler discussed in Section 1.2.3 on page 16.

Unobstructed reflectors are mainly intended for observing planetary details, the moon, and double stars. One of the most appealing features of these designs is that they can be made at home with very simple materials and tools, and yet produce the finest astronomical images.

Note: The effect of surface roughness can be estimated by considering the Strehl ratio = $1 - (6.28\ \mathrm{RMS}/\lambda)^2$, where lambda is the wavelength of light and