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A LITTLE-KNOWN 3-LENS CATADIOPTRIC CAMERA BY BERNHARD SCHMIDT

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Abstract: The authors investigate a prototype 3-lens f/1 catadioptric camera, built in 1934 by the famous optician Bernhard Schmidt at the Hamburg-Bergedorf Observatory in Germany, where Schmidt worked before his death in 1935. The prototype is in the observatory's collection of Schmidt artifacts, but its nature was not understood before the authors' recent examination. It is an astronomical camera of a form known as 'Buchroeder-Houghton', consisting of a spherical mirror and a 3-element afocal corrector lens placed at the mirror's center of curvature. The design is named for R.A. Buchroeder and J.L. Houghton who independently published this and related forms of wide-field spherical-lens cameras after 1942. Schmidt died before he could publish his own design. The authors disassembled the prototype and measured its optical parameters. These they present together with a transmission test of the corrector lens. The authors also consider the theoretical performance of the design as built, the theory of Houghton cameras, Schmidt's possible path to his invention, and the place of the prototype in his scientific output.

Keywords: anastigmat, Bernhard Schmidt, Hamburg Observatory, Buchroeder-Houghton, catadioptric camera

1 INTRODUCTION

Bernhard Schmidt's 1929-1930 invention of the aspheric corrector-plate camera—'Schmidt Camera'—started a revolution in optics and instrumentation which continued for decades after his premature death on 1 December 1935. The Schmidt Camera was the first highly color-corrected, catadioptric anastigmat of great speed ever devised. It could be built in small sizes for use in spectrographs, or in large sizes for astronomical survey telescopes. Its principal difficultty consisted in making the aspheric corrector plate. As is well-known, after 1940 other designers such as Albert Bouwers in Holland, Kurt Penning in Germany, Dmitri D. Maksutov in the USSR, and James L. Houghton in the UK succeeded in replacing the difficult-to-make corrector plate with simpler-to-build spherical lenses (Marx and Pfau, 1992: 24-31; Riekher, 1990: 321-347; Wilson, 2007: 148-217). But what is less widely known is that Bernhard Schmidt himself did the same thing as early as 1934. And what has remained virtually unknown is that Schmidt's resulting prototype 3-lens camera still exists at the Hamburg-Bergedorf Observatory in Germany, where Schmidt worked at the end of his life. The authors of this paper examined it there in November 2007 (see Figure 1).

2 HISTORICAL BACKGROUND

The aspheric-plate Schmidt Camera played a leading role in the technological development of fast wide-field imaging in the twentieth century. This was not only so in astronomy, where it served and continues to serve as an important tool for surveying and mapping the 'deep sky'—one has only to think of the 1.2-meter Oschin-Schmidt Telescope on Palomar Mountain—but also outside of astronomy in fields such as X-ray medical diagnostics, television projection, *etc.*

The principal problem with the Schmidt Camera has always been the formation of a usable aspheric corrector plate. Schmidt's preferred method of making correctors required elastic deformation of the glass plates under a partial vacuum (cf. Schorr, 1936b). This can work well as

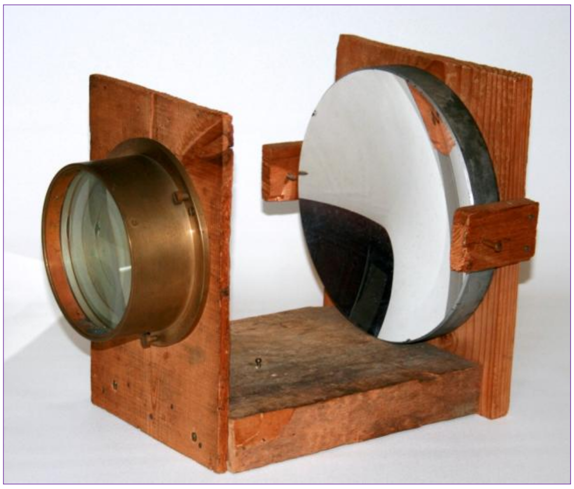


Figure 1: Bernhard Schmidt's prototype camera, consisting of a fast spherical mirror (right), and a 3-lens afocal corrector (left: in a brass lens cell). The optical design is of a type later named 'Buchroeder-Houghton'. Built in 1934, the camera was used by Schmidt to take test images of the sky, shortly before his death (image courtesy: Walter Stephani and the Hamburg Observatory, University of Hamburg).

Figure 2: Bernhard Schmidt (left) and Arthur Arno Wachmann (right) in the summer of 1935 at the Hamburg-Bergedorf Observatory. Wachmann and Schmidt collaborated in the use of the two aspheric-plate cameras that Schmidt built for the Observatory. After Schmidt's death, Wachmann began to compile an archive of documents relating to his life.

Schmidt himself showed in 1930, and as later makers also found (Everhart, 1966; Ohlmüller, 1942). However, the 'vacuum-pan' method of making corrector plates is not without pitfalls, one of which is that the tension induced in the glass plate during deformation can lead to catastrophic failure, when the glass implodes and literally flies to pieces (Cox, 1972: 390-391; Everhart, 1966: 715). Catastrophic failure places a mechanical limit on the extent of elastic bending, and therefore also on the asphericity that may be usefully induced into a corrector plate. This, in turn, constrains the photographic speed. In order to reach speeds faster than about f/1.5, either a change in fabrication methods is necessary, or else a change in the optical system itself (cf. Cox, 1939; the comments by D.O. Hendrix in Ingalls, 1953: 371; DeVany, 1981: 295-296; Riekher, 1990: 327).

Schmidt chose the latter approach. Yet because of his premature death in 1935, when he was on the cusp of achieving fame for his aspheric-plate camera, and also because of his well-attested reserve and secrecy, only a few people at Bergedorf—Richard Schorr, the Director; Arthur Arno Wachmann, an astronomer (Figure 2); and possibly Carl Vick, a staff member—were aware that Schmidt had pushed conceptually beyond the limits of the aspheric-plate camera.

It is true that Wachmann called attention to Schmidt's prototype 3-lens system in articles published in 1955 and 1962, both in the United States (in English) and in Europe (in German and Swedish); and he provided a photograph that depicts the same crudely-mounted instrument as is seen above in Figure 1 (Wachmann, 1955a; 1955b; 1962). Wachmann's photograph is reproduced here as Figure 3. The English-language version of his paper states that:

> … [Schmidt] anticipated increasing the focal ratio to f/1, and, even more, that a lens system would be better than a correcting plate. He made detailed calculations for this and made a first model, a typical wood-and-screw assembly of his which, despite its primitiveness, in the artist's hands took good [stellar] photographs. (Wachmann, 1955a: 9).

The word 'stellar' is added in Wachmann (1962: 32). Nevertheless, since Wachmann's papers provided few concrete details of the construction, optical designers could not easily assess its significance.

Wachmann had worked closely with Schmidt during the last years of Schmidt's life when he was a free-lance consultant (*freiwilliger Mitar-*

beiter) in Bergedorf. Wachmann was also an early and frequent user of the two aspheric-plate telescopes that Schmidt completed there. After Schmidt's death, Wachmann began to assemble an archive of documents relating to his life, starting in the 1940s and continuing for decades. Ultimately, Wachmann passed this archive on to Bernhard Schmidt's nephew, Erik Schmidt, who is still in possession of it. The 'Wachmann-Schmidt archive' is invaluable for any study of Bernhard Schmidt.

One scholar who has studied the archive is Barbara Dufner. She accessed it in 1998 during preparations for her doctoral dissertation, which was later published as a book (Dufner, 2002a). Dufner's study remains the only full, scholarly assessment of Schmidt's optical and scientific work. Erik Schmidt's (1995) own biography of his uncle focuses more on personal and family history. Nevertheless, both books contain a great deal of important information that goes far beyond earlier sketches of Schmidt, revealing the complexity, brilliance, and tragedy of his life (for earlier sketches, see e.g., Hodges, 1948; Ingalls, 1953: 365-373; Silverman, 1950).

Recently, the present authors also were granted access to the Wachmann-Schmidt archive, as part of an ongoing study that they have jointly undertaken. It was at an early stage of their work that they stumbled across the existence of Schmidt's prototype 3-lens camera, which still exists at Bergedorf but has not been understood since Wachmann's time. The discovery occurred in the following way.

3 FINDING THE PROTOTYPE CAMERA

After visiting the Hamburg-Bergedorf Observatory in the northern summer of 2004, we determined on a plan to survey, electronically scan, and study all known evidence (texts, documents, artifacts) relating to Bernhard Schmidt. In addition, we have conducted an extensive search for additional information. Evidence is abundant both at Bergedorf itself and elsewhere in Germany, such as at Mittweida, the town in Saxony where Schmidt lived, studied, and worked from 1901 until the late 1920s. Both the Hamburg-Bergedorf Observatory and the Technikum-Mittweida ('University of Applied Sciences') contain archives with Schmidt documents and artifacts. Early in our joint study, when we first encountered Wachmann's printed articles, we were impressed not only by his words but also by his photograph of the prototype camera (Figure 3).

In her biography of Schmidt, Dufner expressed the idea that, although Schmidt had gone beyond merely conceiving a spherical-lens camera and making drawings and calculations for it, "Only these notes and drawings have been preserved." (Dufner 2002a: 237; our English translation). She also published a synopsis of her book in the popular astronomy magazine, *Sterne und Weltraum*. There she displayed a copy of Wachmann's 1955 photograph, but stated in the caption that it showed a prototype of the correction-plate camera: "Prototype of the Schmidt telescope. With this wooden model, Schmidt tested the effect of [a] correction plate and spherical mirror." (Dufner 2002b: 34; our English translation).

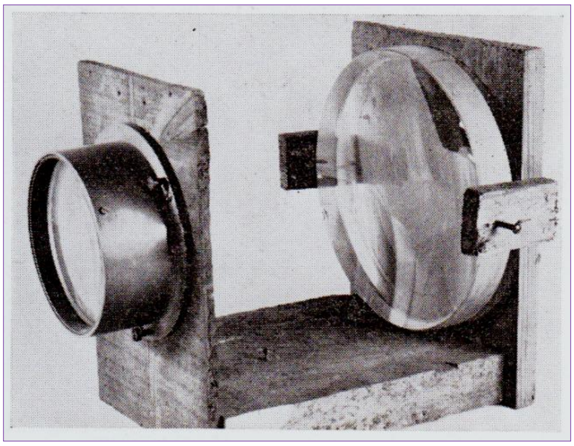


Figure 3: Schmidt's prototype 3-lens camera as shown in Wachmann's 1955 photograph (image courtesy: Ekkehard Wachmann).

Having seen Wachmann's papers, we realized that the great depth of the brass lens cell attached to the wooden upright in front of the mirror must contain not one lens—and certainly not a thin corrector plate—but two or probably three normal lenses. In addition, as a result of intensive document searches we became aware of drawings such as the one shown in Figure 4, preserved in the Hamburg-Bergedorf archive of Schmidt papers. It depicts a deep lens cell containing a triplet composed of one biconcave and two plano-convex lens elements. All the finite

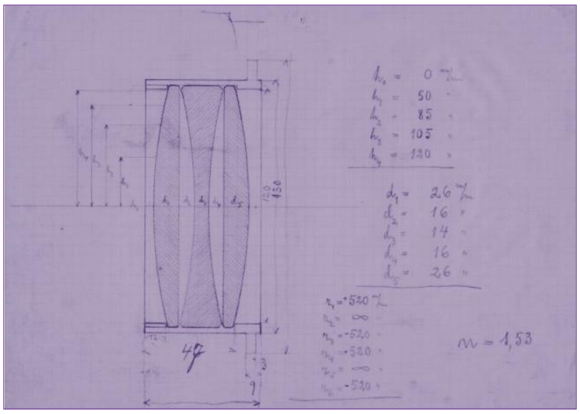


Figure 4: Schmidt's scale drawing of a 3-lens afocal corrector with construction parameters specified. The incidence heights of five rays to be trigonometrically traced are given at upper right (h_0, h_1, h_2, *etc.*). The marginal ray (h_4) intercepts the front lens surface at a radial height of 120 mm, implying a clear aperture of 240 mm (image courtesy Hamburg Observatory, University of Hamburg.

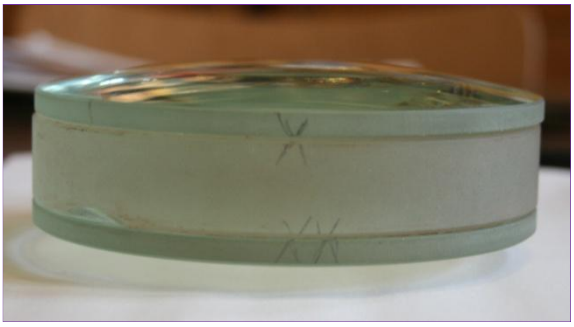


Figure 5: Lens-triplet of the prototype camera removed from its brass cell in 2007. 'Maker's marks' in the form of penciled 'X's' show how the lenses were meant to be assembled. The obvious greenish coloration indicates that common soda-lime 'plate glass' was used rather than expensive optical glass for this prototype instrument (image courtesy: Walter Stephani and the Hamburg Observatory, University of Hamburg.

radii of curvature are listed on the drawing as identical (520 mm). Five incident ray-heights are specified (h_0 to h_4), as well as the axial thicknesses of the lenses and air-gaps (d_1 to d_5). Given these numbers, it is clear that a 240 mm

Figure 6: Wolfgang Busch displays the middle (equi-concave) lens element. On the left of the illustration is the brass lens cell. At the top is the mirror, which is thought to have been aluminized in the 1980s for display when the original Schmidt Museum was opened at the Hamburg-Bergedorf Observatory (image courtesy: Walter Stephani and the Hamburg Observatory, University of Hamburg).

Figure 7: Wolfgang Busch is shown with the spherometer in his left hand which was used to measure the lens radii during the 2007 examination. (image courtesy: Walter Stephani and the Hamburg Observatory, University of Hamburg).

clear-aperture triplet was intended.

Yet at the same time, in a seemingly less formal style of handwriting, the inside diameter of the retaining ring is shown as '120', while the outside diameter of the cell is specified as '130'. The number '47' is written below the lenses. This corresponds to the depth in millimeters of the prototype's cell wall down to the bottom retaining flange. An hypothesis to explain all of this is that initially a triplet of 240 mm clear aperture was projected, but later it was scaled down by one-half to 120 mm, the size of the prototype camera that actually exists.

We therefore obtained permission to disassemble the prototype camera and to inspect and measure its optical and mechanical parts. This we did in 2007 (see Figures 5-7), and again in 2010. Upon disassembling it, we found that the metal cell contained a triplet lens like that depicted in Figure 4, only at half-scale. So the photograph in Figure 3 showed not an aspheric corrector-plate camera, but a novel lens system, just as Wachmann had indicated in his papers.

4 THE BUCHROEDER-HOUGHTON DESIGN

Schmidt did not live long enough to develop his invention further, and never published anything about it. Wachmann's 1955 and 1962 papers appear to be the only indications in print that such a camera ever existed. Thus, it was left to other designers independently to re-invent this optical system, as well as related forms, which they did, starting in 1940.

The first people to publish anything analogous to Schmidt's prototype camera were Robert Richter and Hermann Slevogt in Germany, who obtained a patent announcement in 1941. Their system did not involve a triplet lens like Schmidt's, but rather a doublet of somewhat lesser performance. We shall discuss the optical theory of doublet and triplet designs in a moment. For now let us briefly review the history of their development.

Richter and Slevogt seem not to have published any papers about their design in professional journals, but only to have obtained a patent announcement for Zeiss. Because this occurred during WWII, little or nothing was known of the invention outside of Germany. It was mentioned after the War in a paper published by Horst Köhler (1949: 9 and 16). But Richter and Slevogt themselves only obtained a completed patent in 1954 (Richter and Slevogt, 1954; see Figure 8).

In the meantime, James L. Houghton independently developed more generalized forms of the spherical corrector-lens system, and obtained patent rights both in the UK (1942) and the USA (1944). He also published a paper discussing doublet and triplet forms of his invention in the *Proceedings of the Physical Society* (Houghton, 1945). So although Richter and Slevogt deserve credit for pioneering work, especially outside of Germany attribution for this type of optical system is typically given to Houghton since he was the first to publish in a scientific venue (cf. Wilson, 2007: 213-215).

Houghton's triplet designs are not identical to Schmidt's system, but involve different lens shapes and a much different choice of glass types (see Figure 9). Schmidt's design can thus be viewed as a variant form of a Houghton triplet corrector. The details of the form make it attractive for use in a prototype instrument, since they reduce the number of radii in the total system (including the mirror) to just two, and use just one type of low-index optical glass. Indeed in Schmidt's case, the glass actually employed in the prototype lens is likely just the same as that used for his mirror, namely common soda-lime crown glass.

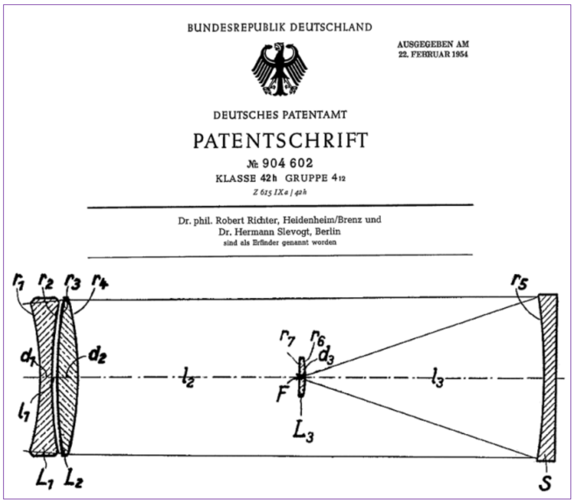
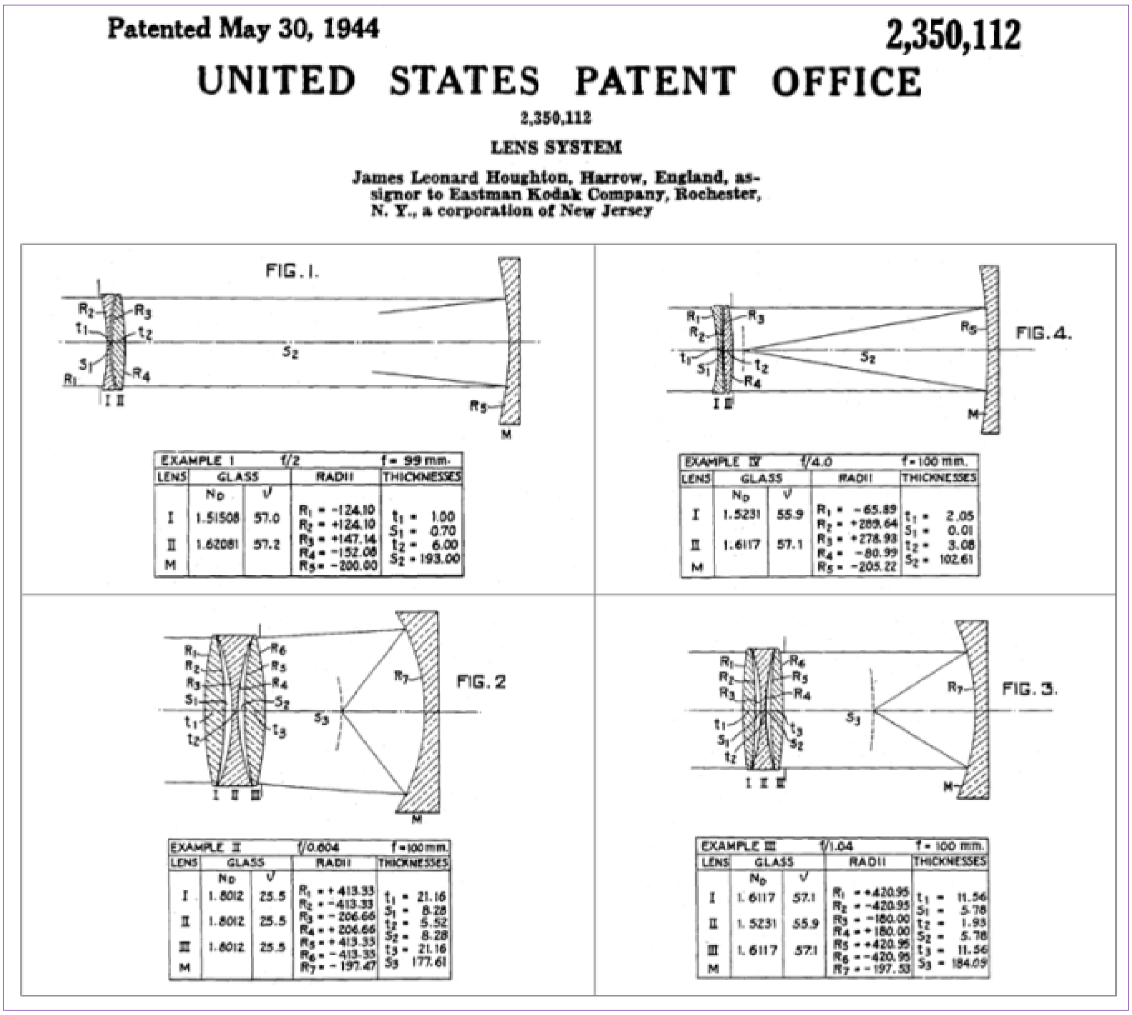


Figure 8: Drawing and title from the completed 1954 German patent of Robert Richter and Hermann Slevogt for a 2-lens afocal corrector plus spherical mirror, similar to the simpler form of the Houghton camera. Richter and Slevogt originally applied for their patent in 1941.



EXAMPLE I	f/2		f = 99 mm.	
LENS	GLASS N_D	GLASS V	RADII	THICKNESSES
I	1.51508	57.0	R_1 = −124.10 R_2 = +124.10	t_1 = 1.00 S_1 = 0.70
II	1.62081	57.2	R_3 = +147.14 R_4 = −152.08	t_2 = 6.00 S_2 = 193.00
M			R_5 = −200.00	

EXAMPLE IV	f/4.0		f = 100 mm.	
LENS	GLASS N_D	GLASS V	RADII	THICKNESSES
I	1.5231	55.9	R_1 = −65.89 R_2 = +289.64	t_1 = 2.05 S_1 = 0.01
II	1.6117	57.1	R_3 = +278.93 R_4 = −80.99	t_2 = 3.08 S_2 = 102.61
M			R_5 = −205.22	

EXAMPLE II	f/0.604		f = 100 mm.	
LENS	GLASS N_D	GLASS V	RADII	THICKNESSES
I	1.8012	25.5	R_1 = +413.33 R_2 = −413.33	t_1 = 21.16 S_1 = 8.28
II	1.8012	25.5	R_3 = −206.66 R_4 = +206.66	t_2 = 5.52 S_2 = 8.28
III	1.8012	25.5	R_5 = +413.33 R_6 = −413.33	t_3 = 21.16 S_3 177.61
M			R_7 = −197.47	

EXAMPLE III	f/1.04		f = 100 mm.	
LENS	GLASS N_D	GLASS V	RADII	THICKNESSES
I	1.6117	57.1	R_1 = +420.95 R_2 = −420.95	t_1 = 11.56 S_1 = 5.78
II	1.5231	55.9	R_3 = −180.00 R_4 = +180.00	t_2 = 1.93 S_2 = 5.78
III	1.6117	57.1	R_5 = +420.95 R_6 = −420.95	t_3 = 11.56 S_3 = 184.09
M			R_7 = −197.53	

Figure 9: Drawings and title from the 1944 United States patent of James L. Houghton for 2- and 3-lens correctors, similar to those in Richter/Slevogt's patent and Schmidt's prototype camera. Note that for his triplets, Houghton employed equi-convex positive lenses, rather than plano-convex as in Schmidt's prototype. In addition, Houghton's system shown as 'Fig. 2' of his patent, although containing just one glass type, employed an extra-dense flint similar to Schott SF6. This would produce a markedly yellow triplet corrector, unsuitable for surveying the night-sky. Houghton's other triplet, shown as 'Fig. 3' of his patent, uses two different crown glass types, unlike the single crown glass of Schmidt's design. Hence, Houghton's patented systems differ in significant details from Schmidt's.

The first person to publish this same design type was Richard A. Buchroeder in the United States. He did it in 1972, having conceived the design and built a set of optics in 1968 (see Buchroeder, 1972; 1980; 1986). For this reason the type of Schmidt's 1934 system is sometimes called the 'Buchroeder-Houghton camera' in English (see Rutten and van Venrooij, 1999: 131-133). Despite the anachronism of applying that name to Schmidt's prototype, for convenience we shall maintain the nomenclature.

5 THE OPTICAL THEORY OF HOUGHTON CAMERAS

The theory of the Houghton or Richter-Slevogt systems is closely related to Schmidt's aspheric-plate camera. Third-order aberration theory predicts that shifting the aperture stop of a spherical mirror to its center of curvature automatically eliminates both off-axis coma and astigmatism (Wilson, 2007: 148-149). Spherical aberration can be eliminated either by use of a figured plane-parallel plate—as in the classical Schmidt telescope—or by use of two or three lenses of zero net optical power. The Richter-Slevogt system uses two lenses, as does the simpler form of the Houghton camera. But more interesting is the use of a symmetrically-arranged set of three lenses.

Analytical equations published by Houghton in his papers show that for any symmetrical arrangement of three thin lenses in the stop position, regardless of the powers of the individual lens (but maintaining zero net-power), to the third order the lens system will contribute no coma or astigmatism (Houghton, 1971-1973). Thus, the Houghton system with a symmetrical triplet corrector can form a wide-angle anastigmatic camera.

Assuming the Buchroeder form of the Houghton design in which the corrector triplet contains one equi-concave and two plano-convex lenses, with a single finite radius of curvature, a single glass type, and zero net optical power, thin-lens theory allows us to derive an exact relationship between the radius of curvature of the lenses and the mirror for spherical aberration control:

$$(1/r_m)^3 = -\,[2(n^2 - 1)(n - 1)/n] \times (1/|r_l|)^3 \qquad (1)$$

where r_m is the mirror's radius of curvature (assumed negative), $|r_l|$ is the finite radius of all the lens surfaces, and n is the n_d index of refraction for the glass. The n-function will equal 1 if $n_d = 1.55139$. Since Schmidt's design shown above in Figure 4 specifies $n_d = 1.53$, r_m should equal $-1.025|r_l|$—or in other words, the mirror should have a radius of curvature 2.5% longer than the lenses. Of course, since Equation (1) is an approximation based on thin-lens theory and is valid only to the third order, in practice it has been found feasible to make the mirror's radius the same as the lenses' when using ordinary crown glasses. If the speed of the system is kept slow enough, performance can still be diffraction limited. Buchroeder's published design came close to this at f/3.

Longitudinal and lateral chromatic aberration are nominally zero in the Buchroeder-Houghton design, since the corrector lens has no net optical power. Field curvature is proportional to the Petzval sum, which is determined by the radius of the concave mirror, just as for an aspheric corrector-plate camera. To the third order, the field curvature is equal to the mirror's focal length. A curved focal surface was not an insurmountable problem in the days of film photography, when the emulsion could often be bent onto a curved platen. This was already done by Schmidt for his earliest aspheric-plate camera (cf. Dufner, 2002a: 225; Mayall, 1946: 287; Schmidt, 1931: 25; 1938: 16). An alternative is to use a field-flattening lens. Whether Schmidt might have done this for his 3-lens camera is not known.

6 SCHMIDT'S PATH TO HIS PROTOTYPE SYSTEM

6.1 Proposal For a 60 cm 2-Lens Camera in 1932

A surviving note by Richard Schorr, the Hamburg-Bergedorf Observatory Director, reveals that already in 1932, that is, about a year after Schmidt's first 36-cm f/1.75 aspheric-plate camera became fully operational, Schmidt was proposing to build a 60-cm 2-lens camera. Schorr's note is preserved in the Wachmann-Schmidt archive (our English translation):

> Schmidt's mirror system 60cm/aperture. 13 April 1932. I resume the discussion with Schmidt about making the 60 cm f/2 mirror system from the available glass disk. Schmidt tells me that he has very recently been busy with the possibility of making an f/1 mirror from the disk. For that purpose, 2 lenses (1 converging + 1 diverging) would certainly have to be used rather than the correction plate: these lenses would be made from simple mirror-glass of about 40 mm thickness. Since the ~~brightn~~ light concentration for extended objects is in this case 4-fold [greater] than at f/2, the change seems very desirable to me, even if the advantage of the longer focal length falls by the wayside. In a few days, we will discuss the business further after mutual reflection.

This 2-lens system is likely to have been a form of Houghton or Richter-Slevogt corrector, possibly consisting of just a plano-convex and a plano-concave lens. Certainly the latter is shown on another of Schmidt's drawings from the period. This is reproduced in Figure 10.

How Schmidt came to the idea of this camera is uncertain. We know from the testimony of Walter Baade (who also worked with Schmidt at Bergedorf), that before he conceived of the aspheric-plate camera, Schmidt had proposed some sort of wide-field system involving lenses. Baade later wrote:

> In 1926 Schmidt had proposed to me to correct the field of a reflector by putting in contact with the mirror a lens of the same size. He was very much in love with this idea but the astronomical trend was against this type of correction, because it would obviously have been impossible to provide lenses of very large sizes. (Ingalls, 1953: 370-371).

Optically, the meaning of Baade's statement is unclear. Literally placing a single lens in contact with a mirror to act as a corrector requires either forming a deep meniscus element, like a Maksutov shell, and setting it against a separate mirror, or else silvering the rear surface of a lens to act as the mirror. The latter type of optical element is called a 'Mangin' mirror. Neither of these possibilities, however, provides enough optical 'degrees of freedom' to correct coma, which was the chief rationale for the design. More probably, Schmidt proposed a different type of construction, which is not clearly conveyed by Baade's words. Possibly it was a Houghton doublet or triplet. Compared to a thin aspheric corrector plate, a thick Houghton lens would be subject to Baade's objection.

Yet a Houghton corrector could hardly be considered as "… in contact with the mirror ..." Instead there would be a significant air-space, as we see in the Houghton-type systems of Figures 1, 3, 9, and 10. If we are to take Baade's words as literally as possible, then another possibility is an *achromatic* corrector, consisting of a crown-flint pair, either placed directly in front of a separate mirror, or with the final lens surface silvered. The last possibility would make an achromatic Mangin mirror. In either case, the doublet could be termed "a lens" and it would be "in contact with the mirror."

6.2 Miethe and the 40 cm Goerz Astrograph of 1914

Before WWI Schmidt had worked extensively with the Royal Astrophysical Observatory at Potsdam, and its Directors, Hermann Carl Vogel and Karl Schwarzschild. Schmidt had also worked with the Berlin optical house of C.P. Goerz, and its client Dr Adolf Miethe, a Professor at the *Technische Hochschule* ('Technical College') *Berlin*. Miethe directed the college's photochemical laboratory. He specialized in the development of panchromatic emulsion and an early system of tri-color photography. He also had a strong interest in astrophotography, and purchased large telescope optics from Schmidt, which he had mounted by Goerz. Letters between Miethe, Schmidt and Goerz survive from the period.

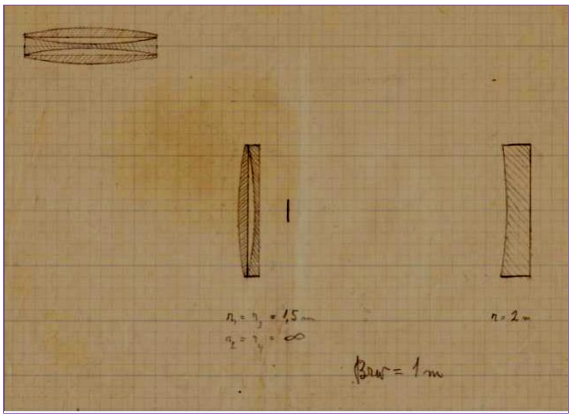


Figure 10: Scale drawing in Schmidt's hand, showing a two-lens corrector (center) and mirror (right). The lenses are plano-convex and plano-concave with finite radii of 1.5 meters; the mirror has a radius of 2 meters. Above left seems to be an alternative idea: a triplet of the Buchroeder-Houghton type (image courtesy: Hamburg Observatory, University of Hamburg).

Miethe had a double-reflector built, consisting of a 30 cm and a 50 cm Cassegrain, with mirrors by Schmidt mounted side-by-side on an equatorial mounting by Goerz (Kühn 2012; Seegert 1927). He used the instrument for many years, praising its optics and even allowing Goerz to show the telescope in its sales literature (cf. Figure 11, after Kühn, 2012: 324). In 1913, the company publicly drew attention to its connection with Schmidt (Goerz, 1913: 12-13; our English translation):

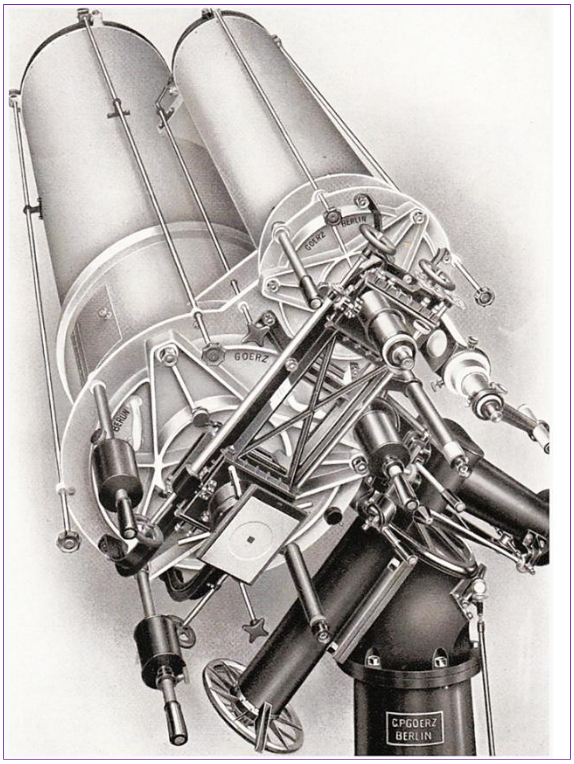


Figure 11: Adolf Miethe's photo-visual double-Cassegrain with 30 cm and 50 cm primary mirrors. The optics were by Schmidt and the mounting by C.P. Goerz. (after Kühn, 2012: 324).

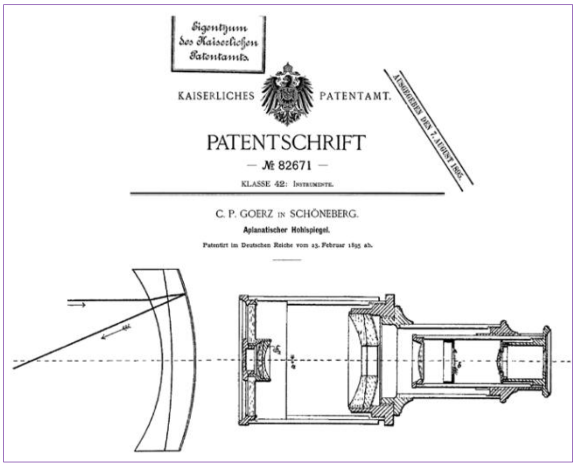


Figure 12: Drawings and title from Goerz's 1895 German patent for an erect-image telescope employing two cemented achromatic Mangin mirrors, each termed an '*aplanatischer Hohlspiegel*' by Goerz. On the left is a blow-up to illustrate the construction of a Mangin mirror. On right is a sectional view of the telescope, constructed in a Gregorian configuration.

> We build larger astronomical telescopes … in all sizes and call special attention to the fact that the well-known workshop for objective-lenses and parabolic mirrors (Cassegrain and other) of Bernhard Schmidt (Mittweida), which enjoys an outstanding reputation in professional circles, has been joined to our optical institute, and that as a result we are in a position to deliver reflectors together with mountings from 200 mm diameter up to the largest sizes.

Privately Goerz (1911) went further, informing Karl Schwarzschild by letter on 10 August 1911 that in future he should send all orders for Schmidt optics directly to them! This amounted to an attempt to commandeer Schmidt's customers, and although Goerz failed in this (Schmidt never agreed to work exclusively for them), it does say something about the closeness of his relationship with Goerz at the time.

Miethe's double-Cassegrain consisted of two standard all-mirror telescopes. But nearly twenty years earlier, in 1895, Goerz had already patented achromatic Mangin mirrors for use in a small erect-image telescope, constructed with a Gregorian configuration (see Figure 12). For this instrument, standard 1st-surface aspheric mirrors were replaced with all-spherical cemented crown-flint lens pairs, the final surface being silvered. The Goerz patent specification emphasizes that with careful glass selection, not only can the Mangin mirrors be individually made achromatic and corrected for spherical aberration, but they can also eliminate off-axis coma "… in a highly perfect manner." The document goes on to say that individual Mangin mirrors can be used at very fast focal ratios down to f/1. In the case of the present telescope, it concludes, by removing

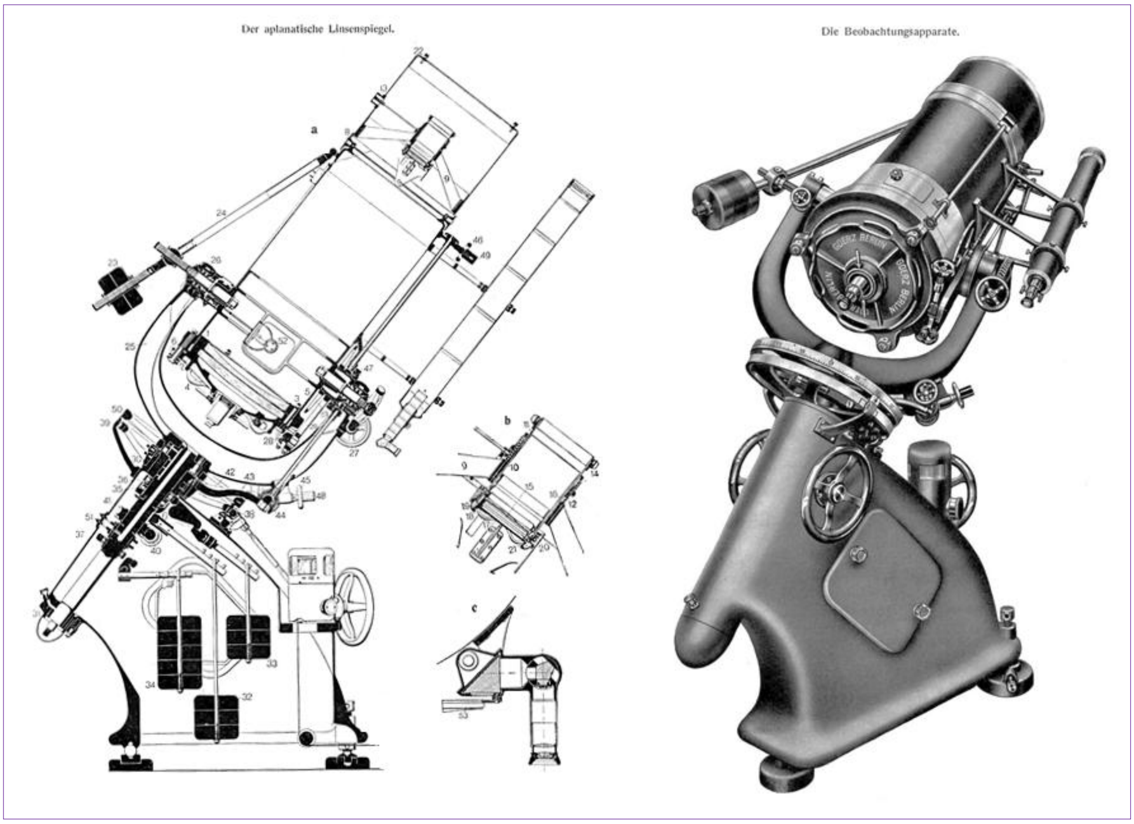


Figure 13: Goerz's 'aplanatischer Linsenspiegel' astrograph, built for Miethe to observe the August 1914 total solar eclipse from Norway. The unit contained a 40-cm air-spaced doublet achromatic Mangin mirror, corrected for coma to give a wide field. On the left of the figure is a sectional view of the astrograph, showing the Mangin at the bottom of the telescope tube. On the right is an exterior representation. By removing the prime-focus photo plate and inserting a second Mangin mirror, the instrument could also be used in Cassegrain mode (after Miethe et al., 1916: 79-80).

the eyepiece and substituting a photo-plate the compound system can also be used as a telephoto lens (Goerz, 1895).

Goerz called such a Mangin mirror an 'aplanatischer Hohlspiegel' (aplanatic concave mirror). Later they changed the term to 'aplanatischer Linsenspiegel' (aplanatic lens-mirror). And they did not stop at small ones. For the August 1914 total solar eclipse whose line of totality crossed Norway, Sweden, and the Russian Empire, Goerz constructed a 40-cm f/3 all-spherical coma-free achromatic Mangin astrograph. It was to be used by Miethe for coronal research at Sandnessjøen in Norway. His colleague, Goerz employee F.M. Weidert, later discussed the instrument in print and illustrated it (Miethe et al., 1916: 71-82; see Figure 13). This instrument was shown as late as 1922 in a published description of Goerz's product-line (Feldhaus, 1922: 366). So the optical configuration of the coma-free Mangin astrograph was technologically current in the years immediately prior to Schmidt's 1926 proposal to Baade.

Although it is not known who figured the optics for Miethe's eclipse telescope, an obvious possibility is Schmidt. He had just successfully refigured the defective 50-cm Steinheil visual achromat for Potsdam. This received high praise from Schwarzschild, who hoped in turn to have Schmidt refigure the defective 80-cm Steinheil photographic objective. But that venture was forestalled by Rudolph Steinheil, using his connections to the German Government, since he feared it would prove a fatal blow to the prestige of his company (Dufner, 2002a: 51-59).

In the event, WWI broke out in the first days of August 1914 and the German astronomers sent to Norway were unable to use the Goerz astrograph for the proposed coronal research and had to return to Germany empty-handed. For Schmidt, however, in Mittweida the situation was far worse. As an Estonian he was considered a Russian citizen and therefore an enemy alien in Germany. He was detained and interned for five months, along with other Russian nationals, in nearby Sachsenburg prison. While there he wrote a postcard to Schwarzschild, dated 26 October 1914, asking for news (our English translation):

> Despite the confusion of the war, I would still be interested to find out what's become of the 80 cm objective lens, and what of the solar eclipse expeditions? In Norway there were also things by me. As a Russian national I have been interned here as a prisoner of war, and can get no information. At the beginning I did hear that the astronomers of the Berlin Observatory were arrested in southern Russia.

What "things" by Schmidt were in Norway is uncertain, but the optics of the 40-cm Goerz astrograph are a possibility. Be that as it may, even if Schmidt did not make these novel coma-free lenses, he must surely have known about them, since he worked so closely with Goerz and Miethe. He had a deep interest in optical design, as well as great skills in fabrication. In speaking with Ejnar Hertzsprung, Karl Schwarzschild went so far as to declare about Schmidt: "He knows more about optics than everyone else put together." (Hermann, 1994: 93).

6.3 The Development of Reflecting Telescopes in the Early Twentieth Century

On other grounds too it is clear that by 1926 Schmidt had long been thinking about alternatives to conventional Newtonian or Cassegrain telescopes for astrophotography. This is not surprising because astronomers had by then sought for several decades to find relief from the off-axis aberrations of their conventional reflectors (coma mainly, but also astigmatism). These errors degraded image sharpness, and made wide-field astrophotography impossible using mirrors. Already in 1905 Schwarzschild (1905: 20-28) himself had made a stab at the problem, proposing a two-mirror coma-free design operating at f/3. Unfortunately, the system had disadvantages which prevented its widespread adoption (see Dimitroff and Baker, 1945: 93-94; Wilson, 2007: 115, 117-119).

Somewhat later, the French designer, Henri Chrétien, working with American optician, George Ritchey, had devised another solution: an unconventional Cassegrain now known as the 'Ritchey-Chrétien' (Chrétien, 1922). After WWII, many Ritchey-Chrétiens were constructed for professional observatories. But their relatively slow speeds (~f/6-f/10) and large plate-scales made them unsuitable for survey work. In the 1930s, Frank E. Ross (1934) at Yerkes Observatory worked out a set of correcting lenses to help to widen the prime-focus field of the 60-inch f/5 reflector at Mt. Wilson, and later also the 200-inch f/3.3 Hale Telescope on Palomar Mountain. But high-performance prime-focus correctors for fast mirrors did not arrive until the 1960s (Wilson, 2007: 348-363).

So at Bergedorf during Schmidt's time there remained a pressing need for a fast wide-field reflecting telescope. Both Baade and Schorr urged Schmidt to think of a solution. Baade, in particular, was hampered in his research on galaxies by the large amount of coma seen on plates taken with the Bergedorf 1-meter f/3 Zeiss reflector (Schramm, 1996: 198). Its field of good image sharpness was only a few minutes of arc in diameter (Ross, 1935: 157-158). Schorr (1936a: 45-46), for his part, desired a still faster reflector of f/2 for wide-field imaging (cf. Mayall, 1946: 283).

Since Schmidt was an accomplished astrophotographer and had been making very fast paraboloidal mirrors for deep-sky imaging since 1905, he was well aware of the problems that coma and astigmatism created in reflecting telescopes (Vogel, 1906a; 1906b). His own interest, however, was high-resolution solar and lunar imaging; and for this type of work, he had devised two solutions by the mid 1920s. One required a very long focal-ratio concave mirror mounted horizontally and fed via a siderostat. To gain access to the image, Schmidt tilted the concave mirror and warped it in a harness to compensate the tilt-induced aberrations. With this 'horizontal mirror-installation' (Horizontalspiegelanlage) he obtained outstanding images of the Moon and sunspots (Schorr, 1936a: 45-46).

A second solution involved what Schmidt termed "… a type of un-pierced sidewise Cassegrain with complete removal of coma and astigmatism despite the oblique layout." (our English translation). The precise nature of this construction is uncertain, but a type of Schiefspiegler seems likely (Dufner, 2002a: 167).

Schmidt announced the "sidewise Cassegrain" to Schorr in June 1926, the same year he first proposed to Baade the correction of a fast wide-field reflecting telescope. Ultimately, whether Schmidt's first proposal was for an achromatic Mangin, like Miethe's 40-cm instrument or something else, Baade curtly rejected the use of large conventional lenses. In a private letter that Baade wrote to Wachmann on 2 June 1955, he stated (our English translation): "I know very precisely his original solution. He was very much in love with it and I rightly ripped it down at the time." The blunt choice of words is noteworthy: Baade put his foot down *firmly* when it came to Schmidt.

Thereafter, Schmidt fell silent for two years, according to Baade's letter. Then suddenly he announced his aspheric corrector-plate camera. The steps in his thought process leading from the lens proposal to the aspheric corrector plate are unknown. Baade questioned Schmidt repeatedly about this afterwards, but Schmidt refused to answer (Dufner, 2002a: 190). Yet it is clear at the same time that Schmidt never forgot the use of lenses as a means of correcting spherical mirrors. After Baade left Bergedorf to take up a permanent position at Mt. Wilson in 1931, and after the success of the aspheric corrector-plate camera, Schmidt returned to the idea of large standard lenses. But this time, instead of placing them in contact with the mirror, he profited from the lessons of the 'Schmidt Camera' and moved them far away. This led to the Houghton-type of telescope.

6.4 Schmidt's Development of Large and Small Houghton Systems

Returning now to Figure 10, what is depicted there is a telescope of 1-meter focal length, since a notation at bottom right of the drawing in Schmidt's characteristic script reads: "Brw = 1 m," in other words, "focal length [*Brennweite*] = 1 meter." A short, dark vertical line placed on the graph paper 2½ divisions to the right of the corrector would seem to mark the position of the focal surface. Since this is exactly 20 divisions to the left of the mirror, the drawing scale is apparently 1 division = 5 cm, that is, 1:10. If so, then the system aperture would be 60 cm and the focal ratio would be f/1.67, closely matching Schorr's 1932 suggestion. But note also at upper left in Figure 10 a triplet lens consisting of one equi-concave and two plano-convex lenses —in other words, a Buchroeder-Houghton corrector. Unfortunately the drawing is undated.

The ambitious size of Schmidt's proposed systems as well as the rather hazardous notion of employing common soda-lime 'mirror-glass' instead of precision optical glass for the thick doublet (or triplet) corrector may have dissuaded Schorr from final agreement. Money was naturally tight since the years of these developments coincided with the worst part of the Great Depression. In any case, Schorr had another idea which he determined to implement using the available resources. He wanted to build a 'double reflector' consisting of a 60-cm f/5 conventional Newtonian telescope teamed with an identically-sized Schmidt aspheric-plate camera. With this he hoped not only to obtain coma-free images on a larger plate scale using the Schmidt camera, but probably also he wanted to show its decisive superiority over the Newtonian (Dufner, 2002a: 253-263; Schorr, 1936a: 45-46). The astronomical world had not beaten a path to the Hamburg Observatory after the initial announcement of Schmidt's revolutionary coma-free telescope (cf. Baade's remarks in Ingalls, 1953: 371).

Unfortunately, the combined double reflector (completed in 1935 and housed in a roll-off roof shelter) was so easily shaken by the wind that good exposures were almost impossible to obtain. A.A. Wachmann, one of the principal observers to use this telescope (for many years the largest Schmidt camera in the world), later termed it "the still-born child" (das totgeborene Kind—a hand-written notation on a photograph in the Wachmann-Schmidt archive; cf. Dufner, 2002a: 262).

As for Schmidt's spherical-lens cameras, they soon evolved toward smaller sizes. Figure 14 shows the only complete drawing from Schmidt to depict one of his Buchroeder-Houghton designs at scale (Hamburg-Bergedorf archive; cf.

Dufner, 2002a: 235). The focal length is listed as 62.5 cm, and all the radii are listed as 1250 mm. Since the position and diameter of the focal plane or film platen are clearly shown at the drawing center, we can see that the scale of the drawing is about 2.5 cm per division of his graph paper. From this we can deduce the size of the corrector triplet as 400 mm, and the mirror diameter as 475 mm. The film platen would be 100 mm in diameter.

But even this was apparently deemed too large, and in a packet of drawings and trigonometric calculations in the Hamburg-Bergedorf archive of Schmidt documents, dated 4 May 1934, there is a corrector 240 mm in diameter. This was shown above in Figure 4. Another page of the packet gives a corresponding dimensional drawing of the lens cell. In addition, the packet contains detailed trigonometrical ray-traces of the system for five ray heights in the entrance pupil. Longitudinal intersection lengths are calculated, and then graphed to show the higher-order spherical aberration error curve.

Who it was that performed the ray-tracing is unclear. The handwriting is not Schmidt's, being far less legible. Probably the answer is Carl Vick, a Bergedorf staff member who is known to have performed ray-tracing for Schmidt in connection with the double reflector, a project which was ongoing in 1934.

In the end, a further reduction of the triplet corrector camera to 120 mm clear aperture was decided on, and that is what was actually built. A new ray-trace was not needed since all the geometrical ray errors simply scaled down by one-half. Figure 15 reproduces the first page of notes connected to the ray-trace of the 240 mm version. The page is entitled: "Ray-tracing formulae for the Schmidt mirror with pre-placement lens" (Durchrechnungsformeln für den Schmidt'schen Spiegel mit Vorsatzlinse). A complete design is specified, utilizing one equi-concave and two plano-convex lenses, all of mean refractive index 1.53. A notation is added to the effect that the mirror radius—to first approximation—should be the same as the finite lens radii, namely 520 mm, but in case the mirror's radius is altered, its center of curvature should still coincide with the center of the 'pre-placement lens' (i.e. the corrector) by altering the air-space between the last lens element and the mirror (d_6 in the drawing). In fact, further up the page of notes we see that the mirror's radius was taken as 542 mm for the purposes of the ray-tracing. How this number was arrived at is unclear. Equation (1), given earlier in this paper, would predict 533 mm for a corrector with refractive index of 1.53.

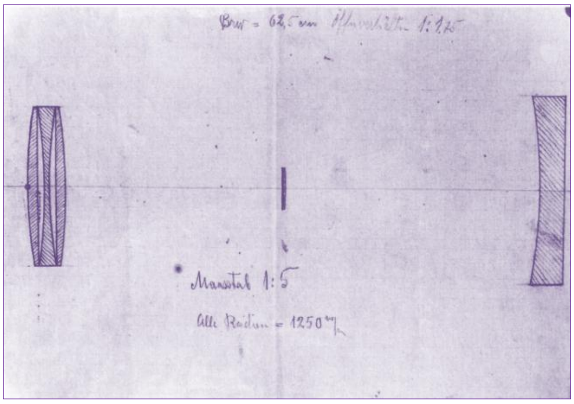


Figure 14: The only surviving scale drawing in Schmidt's hand for a full Buchroeder-Houghton camera. The focal length is listed as 62.5 cm and the drawing scale is 1:5. The notation at upper center-right, "Öffn[ungs]verhältn[is] 1:1.75" appears not to be in Schmidt's hand (image courtesy: Hamburg Observatory, University of Hamburg).

6.5 Symmetry and the Plane-Parallel Plate

However it was that Schmidt arrived at the idea of the Buchroeder-Houghton, he likely started from considerations of symmetry. Symmetry lay at the heart of his coma-free aspheric-plate cam-

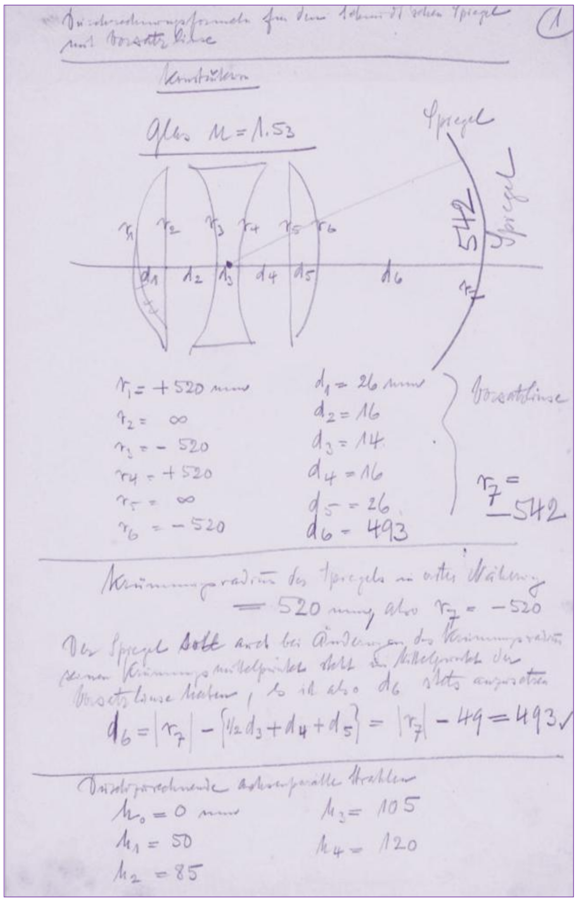


Figure 15: A page of notes accompanying the trigonometrical ray-trace of a 240 mm f/1.1 Buchroeder-Houghton camera. The notes contain a complete system prescription. All the finite lens radii are set at 520 mm, and the mirror's radius at 542 mm. Rays at normalized incidence heights of 0% (paraxial), 41.7%, 70.8%, 87.5%, and 100% (marginal) are traced on the following pages of notes in the packet (image courtesy: Hamburg Observatory, University of Hamburg).

era, and Schmidt understood the connections between optics and pure geometry. The greater the symmetry of a set of imaging optics around its aperture stop, the smaller in general will be the residual geometrical aberrations. Complete symmetry automatically eliminates coma, astigmatism, lateral color, and distortion. Lens designers have long utilized symmetry to design camera optics; in theoretical discussions, they speak of 'the symmetrical principle' (Smith, 2000: 401). Schmidt's aspheric-plate camera succeeded so admirably because it is almost completely symmetrical about its aperture stop; only the introduction of the plate's asphericity creates a weak axis that degrades symmetry. If the aspheric plate were to be discarded—or turned into a plane-parallel 'window'—leaving only the spherical mirror plus aperture stop as effective optical elements, the system would be perfectly symmetrical about the stop and hence would suffer none of the off-axis aberrations mentioned above. It would be afflicted with just spherical aberration and field curvature.

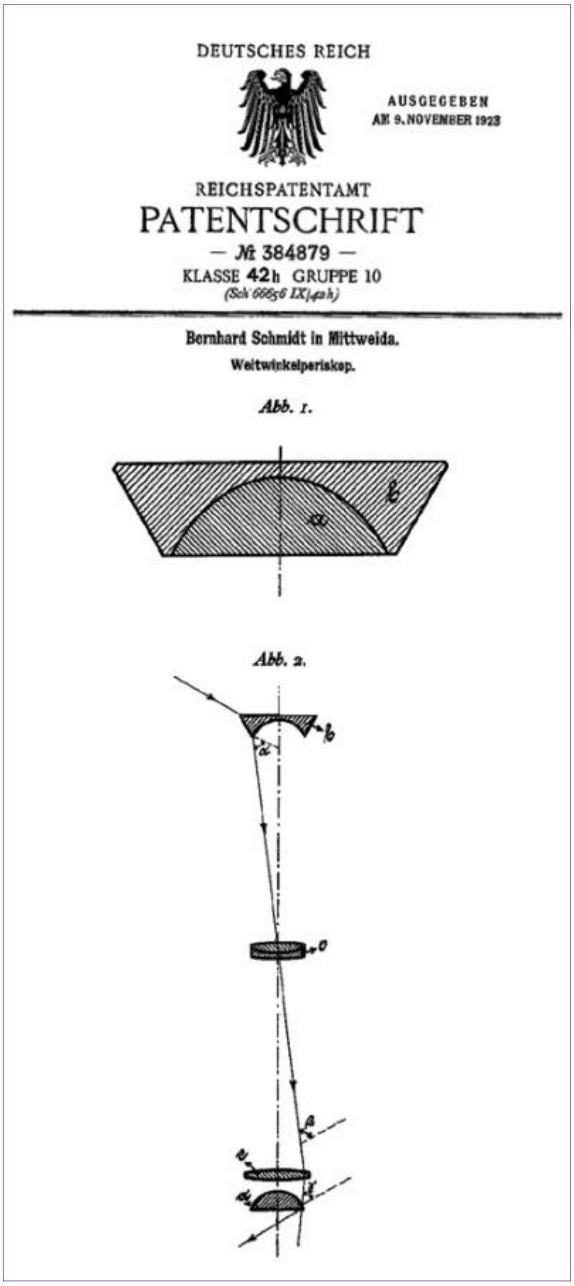


Figure 16: Drawing and title from Schmidt's 1923 German wide-angle periscope patent. The upper illustration (*Abb. 1*) shows how the plano-concave (b) and plano-convex (a) lenses conceptually fit together to form a plane-parallel plate.

The Buchroeder-Houghton corrector is a nearly symmetrical construction, if the aperture stop is placed on the middle lens element. It resembles a Cooke triplet lens, the most economical anastigmatic camera lens ever devised (Conrady, 1960: 817-818). But while the Cooke triplet must converge light to a focus, the Buchroeder-Houghton corrector exists only to contribute overcorrected spherical aberration which cancels the undercorrected aberration arising from the spherical mirror. At the same time, the corrector must not introduce other image errors. So it is given net-zero optical power which avoids longitudinal and lateral chromatic aberrations, and an overall symmetrical shape which avoids off-axis monochromatic aberrations.

Returning to the notion of a plane-parallel plate, Schmidt recognized that bundles of parallel rays traversing a flat plate suffer no aberration, even when they arrive at oblique incidence. But the plate can also be imagined as consisting of two lenses, one plano-concave, the other plano-convex, with their curved surfaces fitting one another exactly. The surfaces can even be mating aspheres and still the transmitted bundles will pass without aberration.

Schmidt had employed this idea as the basis for his invention of the wide-angle periscope that he patented in 1923. The patent drawing for this device is shown in Figure 16. Toward the top of the figure (*Abb. 1*) we find the plano-concave and plano-convex lenses fitted together, forming between them a plane-parallel plate. Schmidt's essential insight was that if these two lenses are separated and a relay lens of unit magnification is set between them—imaging the concave lens onto the convex—then by the proper choice of curves this simple device can act as a 1× periscope covering a visual angle of 120º with excellent sharpness. It lies beyond the scope of the present paper to explore this design in greater detail, but suffice to say that modern computer ray-tracing easily confirms Schmidt's claims.

The idea of a plane-parallel plate also figures in Schmidt's aspheric-corrector camera, as indicated above. Schmidt set a thin parallel plate at the center of curvature of a spherical mirror and figured an axisymmetric polynomial profile onto it, of such a form that it compensated the mirror's spherical aberration. This yielded a revolutionary instrument: the Schmidt Camera. But alas, it has physical limits imposed by the material strength of the glass, if a vacuum-pan is used to fabricate the corrector plate. If there is too much surface deflection under pressure the plate will shatter.

Still another use for a plane-parallel plate is to imagine that it consists of a plano-convex and plano-concave lens in contact—but now with the convex lens appearing first in the light path. Both lenses would be positioned at the center of curvature of a spherical mirror. In effect, they would form a 'lensless' Schmidt Camera, fitted with an optical window instead of an aspheric corrector plate (Ashcraft 1974). If the convex lens element is now reversed so as to point its convex face forward, towards the oncoming light and away from the concave lens, then together the two lenses would still exhibit no net optical power, but the changed lens orientation would drastically alter the combined spherical aberration. In particular, the convex lens would contribute far less undercorrected spherical aberration than in its former orientation. The balance of aberration would tip in favor of the concave lens, and the pairing as a whole would introduce *overcorrected* spherical aberration into the system—just what is needed to compensate the undercorrected aberration of the spherical mirror. Proper choice of radii (keeping lens curves equal but opposite, and using a single type of glass) can produce good compensation. This is the rationale behind the two-lens Houghton camera.

But unfortunately, this corrector lacks constructional symmetry. Coma and astigmatism cannot be eliminated by placing this two-lens corrector at the mirror's center of curvature as the system stop. Either it must be shifted from the center of curvature, or additional degrees of freedom (lens radii, glass types, asphericS) must be utilized. Schmidt himself seems to have understood this, since his doublet corrector as shown above in Figure 10 has been displaced from the mirror's center of curvature to a position near its focus (cf. Figure 9, upper right, for J.L. Houghton's analogous design). It lies beyond the scope of the present paper to delve more deeply into the design of two-lens Houghton or Richter-Slevogt telescopes. For further information, see Lurie (1975), Rutten and van Venrooij (1999: 299-300) and Sigler (1978).

A way to circumvent this problem is to reflect the doublet around its plano-concave element. One then obtains a symmetrical 3-lens construction of the Buchroeder-Houghton type, which is capable of very good off-axis performance when set at the spherical mirror's center of curvature. Indeed, in more elaborate forms this 3-lens design is *superior* to the corrector-plate Schmidt camera (e.g., in the Baker-Nunn camera; see Carter et al., 1992; Henize 1957).

That Schmidt may have proceeded conceptually from a plane-parallel plate to his two-lens and thence to his 3-lens corrector is suggested by another drawing in the 4 May 1934 packet of papers. This is shown as Figure 17. It appears on the reverse of the sheet already illustrated above as Figure 4—in other words, on the reverse of Schmidt's scale drawing of his 240 mm Buchroeder-Houghton corrector. In Figure 17, the plano-convex lenses have been reversed and the ensemble drawn as a plane-parallel plate, resembling the similar drawing in the wide-angle periscope patent.

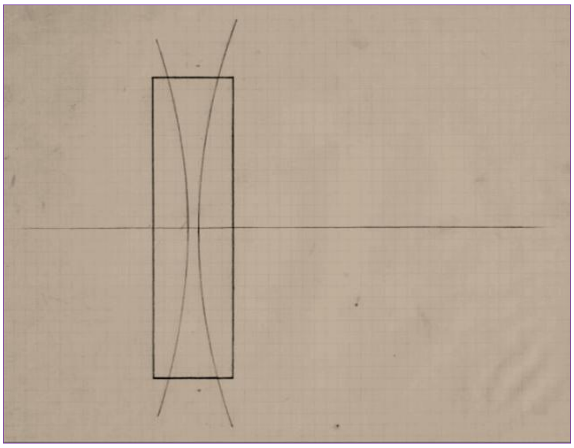


Figure 17: Reverse of the drawing shown previously as Figure 4. Here the plano-convex lenses of the Buchroeder-Houghton triplet have been inverted so that the ensemble forms a plane-parallel plate. In this orientation the glass will produce zero spherical aberration in transmitted parallel light (image courtesy: Hamburg Observatory, University of Hamburg).

7 MEASUREMENTS AND TESTS

Despite the uncertainty of how Schmidt arrived at his designs, he did build a 3-lens prototype and tested it in 1934, according to A.A. Wachmann. This is the instrument that we examined in the Schmidt Museum at Bergedorf and measured in 2007. Figures 6 and 7 above show the work in progress. We measured the surface *sagittae* using a precision spherometer, and then calculated the radii of curvature. We also measured other constructional parameters. These are presented in Table 1, where the numbers are expressed in millimeters.

As can be seen, the design matches rather closely the one-radius form of the Buchroeder-Houghton camera. The divergences in the case of the lens radii may have resulted either from spherometer inaccuracy or slight grinding and polishing errors. They can be shown by optical ray-tracing to have little effect on the final result. One must remember that this prototype was built for photographic purposes and so did not need to form diffraction-limited images.

Table 1: Our measured construction parameters for Schmidt's 1934 3-lens catadioptric camera. The old Schott optical glass 'O15' is conjectural (see the text), chosen to model the probable properties of Schmidt's soda-lime 'mirror glass'. The back focal length, curvature of the image surface, and image diameter are derived parameters.

Surface	Radius (mm)	Thickness (mm)	Glass	Diameter (mm)
Object				0
1		50		----
2	260.4	13	[O15]	125
3		7.3		125
Stop	–261.7	6.8	[O15]	125
5	261.7	7.3		125
6		12.8	[O15]	125
7	–260.4	243		125
8	–266.0	–130.192	Mirror	218
Image	–118.946	-----		28.6

Of more significance to the performance is the radius of the mirror. This was found to be 266 mm, while Equation (1) would predict 267.6 mm (assuming an average lens radius of 261.1 mm, and an n_d glass index of 1.53). The difference between the measured mirror radius and the theoretically-correct number is already enough in principle to cause a perceptible under-correction of spherical aberration. Despite this, the 'as-built' parameters would give reasonable prototype performance. For the purposes of completing our engineering model we have assumed the old Schott glass O15, a crown type with the constants, $n_d = 1.53088$ and $v_d = 58.99$. The actual properties of the glass in the prototype are not known, but its greenish coloration suggests common soda-lime 'plate glass', which was widely used at the time to make mirrors. Such glass would be similar to O15. The ray-trace drawing shown in Figure 15 specifies a glass with $n_d = 1.53$.

Figure 18 presents a schematic layout according to the parameters of Table 1. In principle, the diameter of the prototype's mirror (218 mm in clear aperture) allows a field of 20° (± 10°), covering a curved film platen 47 mm in diameter. That is what is shown in Figure 18. For the purposes of image evaluation, however, in succeeding diagrams the field has been reduced to 12° (± 6°), since beyond that the geometrical images begin to swell noticeably.

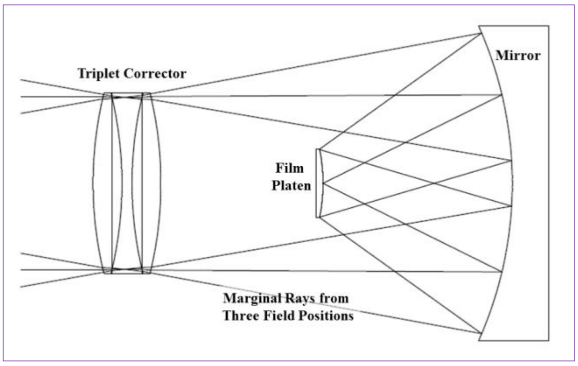


Figure 18: Schematic layout of the 120 mm f/1.1 prototype Buchroeder-Houghton camera as built. The mirror would allow a field coverage of up to 20° on the sky, but with considerable fall-off in edge sharpness. Over a more limited field of 12°, image sharpness is good.

7.1 Theoretical Imaging Properties

Figures 19 and 20 show the theoretical imaging properties of the camera according to the as-built parameters given in Table 1. For reference we should note that typical emulsions intended for faint-light detection in astronomy before the 1980s had rather coarse resolution. For example, the Kodak 103a series of plates, which were used in the first Palomar Sky Survey on the 1.2-meter Oschin-Schmidt Telescope, were rated to resolve 80 line pairs per millimeter, giving a resolution of 12.5 microns (Everhart, 1981: 100; Hartley, 1994: 118). Since for round images, the resolution is one-half the diameter of the image, this means that the smallest images recorded with these emulsions were about 25 microns across. Moreover the reciprocity failure of films meant that only the image cores would actually be recorded for fainter stars. Bright stars, on the other hand, would appear as 'burnt-in' spots many times larger than their actual image size, due to diffusion of light in the emulsion. In addition, 'halation' would create 'halos' of light around these burnt-in images (Kodak, 1987: 30-31, 37-39).

The upshot is that the size of the geometrical spots seen in Figure 19 should not be taken too seriously. In the case of most stars, only the bright cores would actually register, and these are in general only about 25-30 microns in extent over the field evaluated. Bright stars, on the other hand, would show images much larger than 30 microns, regardless of the geometrical spot size. Hence, the imaging properties of this crude prototype camera were in principle good by the standards of the 1930s, and justified A.A. Wachmann's statement that the camera, "despite its primitiveness, in the artist's hands took good photographs." (Wachmann, 1955a: 9).

Figure 20 shows the transverse ray-fan plots according to the as-built parameters. The main residual aberrations are 3rd- and higher-order spherical aberration across the field (balanced against defocus), and coma and astigmatism off-axis. Traces of other aberrations are also present. The 3rd-order spherical aberration is caused mainly by the non-optimum mirror radius, which as we noted previously is too short. Coma mainly results from a non-optimum separation of the mirror from the corrector. This should be enlarged by about 5 mm compared to the as-built separation of 243 mm. The error is small, and an adjustment of the existing collimation screws located behind the mirror would allow for this re-spacing. But in any case, especially in blue and green light, the colors to which the 1930s astronomical emulsions were most sensitive, the image cores are small enough over a 12° field to

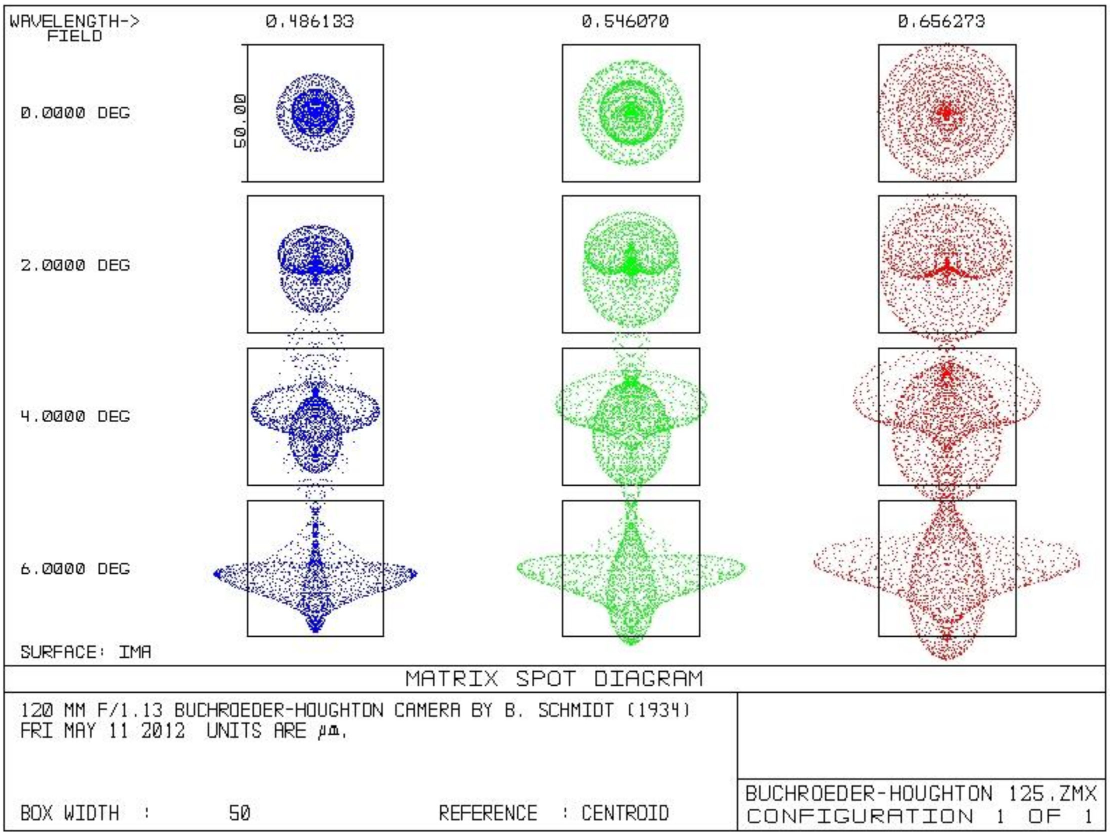


Figure 19: Geometrical optics spot diagrams for three wavelengths (486 nm, 546 nm and 656 nm) and 4 field positions (on-axis and at 2°, 4°, and 6° off-axis) of the 120 mm f/1.1 Buchroeder-Houghton camera as built, referenced to a curved image surface. The image cores of the spots are small enough that stars would look satisfactorily sharp on the astronomical emulsions of the 1930s.

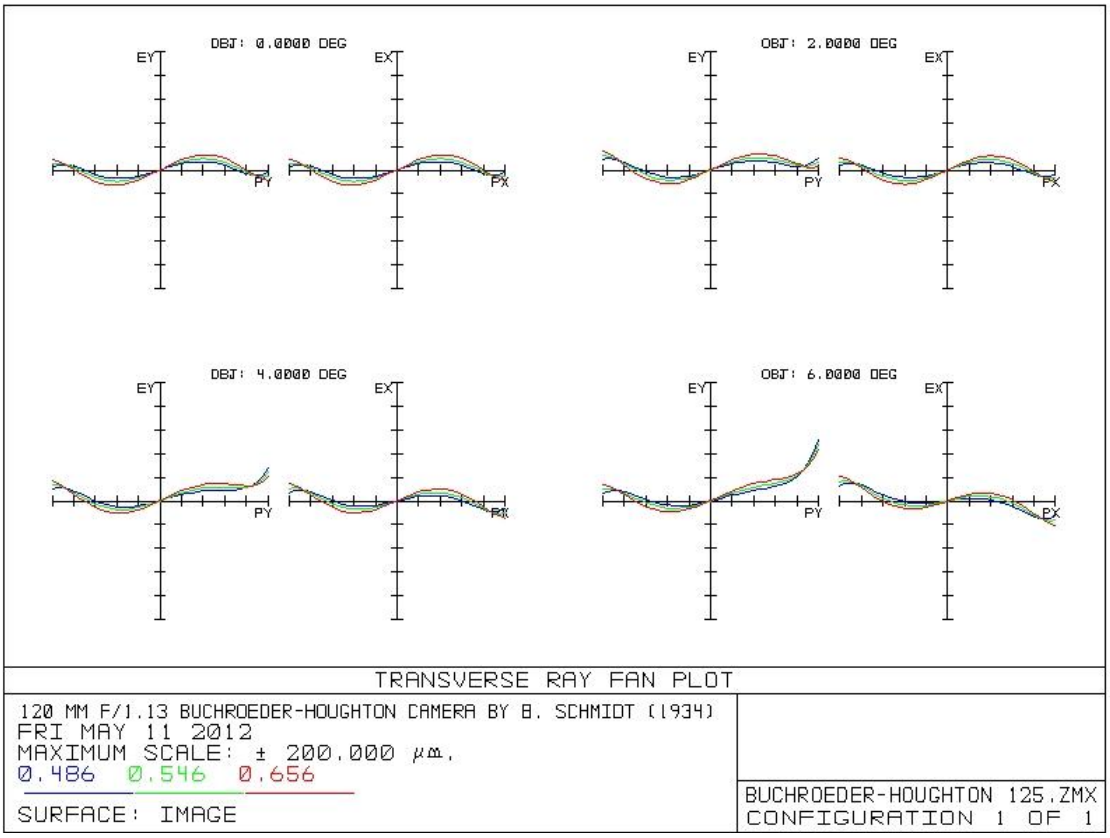


Figure 20: Transverse ray-fan plots for the Buchroeder-Houghton camera, referenced to a curved image surface. The on-axis error curves show the characteristic sinusoidal shape of a slight, undercorrected 3rd-order spherical aberration (plus defocus), and its chromatic variations. Off-axis are seen principally the effects of residual coma and astigmatism, in addition to the spherical aberration.

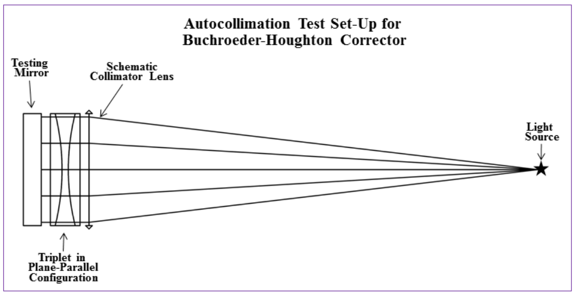


Figure 21: Schematic layout for testing a Buchroeder-Houghton corrector lens. The corrector elements are set into their 'parallel-plate' configuration. On right is a light source. Rays proceed from the source to a collimator lens, represented schematically in Figure 21 as a line with arrowheads at its tips. After passage through the collimator, the light traverses the corrector triplet and arrives at a testing flat on left. After retro-reflection, the light bounces back to a point beside the source where it can be viewed through a Ronchi grating or by means of another testing device.

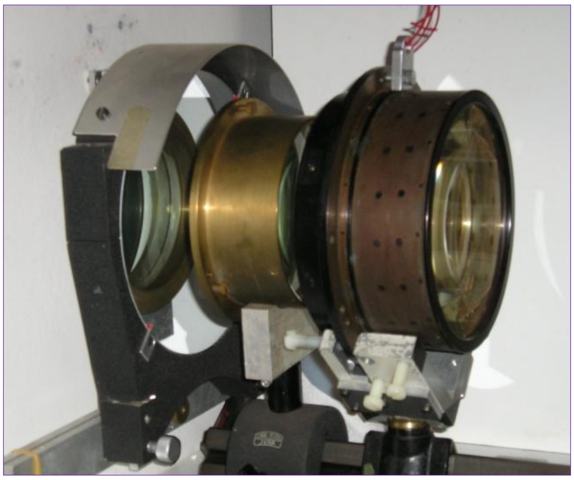


Figure 22: Our actual test set-up. A ZEISS-B apochromat, on the right, acts as a collimator from the light source into the lenses of the Buchroeder-Houghton corrector. On the left is an aluminized autocollimation flat, which receives the light and reflects it back through the system to a point beside the light source (image courtesy: Wolfgang Busch and Walter Stephani).

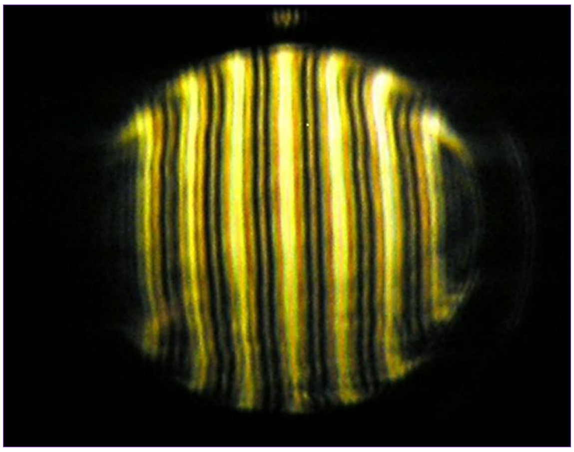


Figure 23. Test results using a Ronchi grating of 2 lines/mm, and testing configuration involving a double passage of the light through the lenses. Straight fringes in the test-image would indicate a spherically-converging wavefront and therefore a sharp focus (image courtesy: Wolfgang Busch and Walter Stephani.)

register as essentially perfect (on a curved film surface)—assuming that the lens and mirror figures were good, and that the homogeneity of the 'plate glass' was not overly bad.

7.2 Optical Testing Methods

Testing of the lens figures and homogeneity may be accomplished in a surprisingly easy way. We noted earlier that Schmidt's conceptual process for developing his Buchroeder-Houghton triplet might have begun with a plane-parallel plate, out of which he 'scooped'—so to speak—two convex lenses. These were then reversed in order to obtain lens bendings that minimized the under-corrected spherical aberration of the convex lenses, while leaving the overcorrected spherical error of the concave lens intact.

With this model in mind, we can easily see that it should be possible to restore the 'original' lens orientations, 'reassembling' so to speak the plane-parallel plate. Doing this should nullify the corrector's spherical aberration in parallel light, if the glass is good and the lenses correctly formed. In order to test the glass, one could utilize a collimator lens and an autocollimation flat. Light from a pinhole or slit source would proceed to the collimator, and after transmission would emerge in a parallel bundle. The bundle would proceed through the corrector lenses set in 'plane-parallel configuration', and finally arrive at the flat mirror. After reflection by the mirror, light would proceed back through the system and arrive at the focus.

Quantitative results could be derived using a laser interferometer, if one were available, but a Ronchi tester or Foucault knife-edge could also give a useful qualitative test. In particular, the Ronchi tester with its diffraction grating will generate the appearance of dark and light bands running across the optics under test. If the bands appear perfectly straight, it means that the transmitted wavefront is spherical and converges precisely to a focus. Any deviation from straight bands indicates aberration. Since the light passes twice through the lens system, any errors appear doubled. Of course the flat and especially the collimator lens must be of high quality so that their optical errors do not confuse the testing. Figure 21 shows a schematic layout of the testing configuration just described.

During the examination of the Buchroeder-Houghton camera, we tested the corrector triplet in just this way, using a large ZEISS-B apochromat as the collimator. The arrangement is shown in Figure 22, where on the right is the ZEISS-B, at the center is the Buchroeder-Houghton triplet in 'plane-parallel plate' configuration in its brass lens cell, and on the left is an aluminized autocollimation flat. Out of the picture, on extreme right, is the light source and Ronchi tester.

Figure 23 shows an image of the test results. Completely straight dark and light bands would indicate a perfect test result. Although these were not obtained, nevertheless the deviations from straightness are relatively small. We must remember first that the test was conducted in 'double pass', that is, with a double passage of the light through the optics. This means that the apparent errors in the wavefront will be double their magnitude when the lens system is in actual use. If we mentally 'unbend' the bands by 50%, they will obviously become much more linear.

And secondly, the lenses are not made of precision optical glass, but 'mirror-glass'. This means that the homogeneity in the index of refraction could easily be uneven in the substance of the glass. Some of the error in band straightness, particularly the high frequency kinks toward the bottom of the image, could be attributable to this source. Despite the possible testing errors, the bands appear remarkably straight nearly to the periphery of the image. Although they clearly betray a 'rolled off edge' in their sudden kinking at the periphery, it is clear that the corrector should perform nearly as well as suggested by the spot diagrams in Figure 19.

8 CONCLUDING REMARKS

On the basis of our examination of these optics, we may conclude that Schmidt's novel camera should have performed reasonably well by the standards of the 1930s, and had he lived longer he might be remembered not just for his epoch-making aspheric-plate camera, but for taking the first steps beyond it toward still faster imaging systems using only spherical optics. Certainly he would be credited with the invention of the Buchroeder-Houghton camera, and possibly he would have developed more general Houghton-type systems. It is important to remember that for several decades (in the 1950-1970s) the fastest wide-field imager in use for scanning the skies was the Baker-Nunn satellite tracking camera, which is an elaborated form of the 3-lens Houghton system (Henize, 1957). Thus the design form pioneered here by Schmidt had great intrinsic significance, and found important applications later in the twentieth century.

Documentary evidence reviewed by Dufner in her book shows conclusively that Schmidt was in the midst of a great burst of design creativity at the end of his life. Not only did he conceive and build this remarkable all-spherical f/1 camera, but he also conceived and proposed to build what we now think of as the 'Schmidt-Cassegrain', and a form of catadioptric Cassegrain using a sub-aperture Mangin mirror for the secondary mirror. This might have been analogous to the 'Klevtsov-Cassegrain', or J.L. Richter's 'Acme Telescope' (Klevtsov, 2000; 2004; Richter, 1981). What is clear is that continued study of Schmidt will certainly reveal more surprising details about his fascinating life and creativity.

9 ACKNOWLEDGEMENTS

We wish to thank the staff of the Hamburg-Bergedorf Observatory for assistance, and the administration for permission to disassemble, measure, test, and photograph the 3-lens prototype camera in 2007 and again in 2010, as well as for permission to publish these results together with images of the camera and Schmidt documents found in their archives. We also wish to thank Erik Schmidt for permission to access and quote from materials found in his archive relating to his uncle. We further thank the *Niedersächsische Staats- und Universitätsbibliothek* (Göttingen University) for permission to quote from the papers of Karl Schwarzschild; and Ekkehard Wachmann for permission to reproduce Figure 3. And finally, we thank Professor Manfred Steinbach and Dr Andrew Rakich for valuable feedback on earlier versions of this paper. All remaining errors are solely our responsibility. An earlier version of the paper was published in German (see Busch, Ceragioli and Stephani, 2011), and we thank Professor Steinbach for permission to revise, expand and pubish an English-language version of that paper.

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11 APPENDIX: BIOGRAPHICAL NOTES

11.1 Wilhelm Heinrich Walter Baade (1893–1960): Astronomer and astrophysicist. After graduation from Göttingen University in 1919, Baade was employed at Hamburg Observatory from 1919 to 1931. In 1926-1927, he travelled to the USA on a Rockefeller Foundation grant. Later he was employed at Mt Wilson and Palomar Observatories from 1931 to 1958. Baade studied stellar populations and galaxy structure, and made important contributions to the distance scale of the Universe. He was a friend of Bernhard Schmidt, and contributed to the introduction of the Schmidt telescope in the USA.

11.2 Richard Alfred Buchroeder (b. 1941): Optical designer and proprietor of Optical Design Service. Buchroeder holds a Ph.D. in optical sciences from the University of Arizona (1976), as well as 13 patents. He is the author of numerous publications, and specializes in the design of innovative optical systems. He works with large astronomical observatories. In 1972, he announced development of a simplified 3-lens Houghton-type catadioptric camera, identical in form to Schmidt's unpublished 1934 system.

11.3 James Leonard Houghton (1911–1995): Optical designer and theorist. Houghton worked for more than 30 years at Kodak Ltd. in the UK. In March 1941, he applied for a British patent on a catadioptric camera with a corrector consisting of two or three spherical lenses to replace the aspheric corrector plate of the Schmidt telescope. He obtained a United States patent for the same invention in 1944. He published papers on the theory of his designs in 1945 and 1971-1972.

11.4 Robert Richter (1886–1956): Optical designer. After graduating from Göttingen University, Richter worked at Voigtländer from 1914 to 1923. Then he joined C.P. Goerz, until Goerz merged with Zeiss-Ikon in 1926. Richter then worked for Zeiss until his death in 1956, serving as the chief of Zeiss's photographic division from 1939 to 1945. After resettlement in Heidenheim following WWII, he participated in building the West-German branch of Zeiss at Oberkochen. His work centered principally on aerial reconnaissance lenses, but also binoculars, and film projection and microscope optics. Together with Hermann Slevogt, he developed an all-spherical 2-lens catadioptric camera which anticipated the work of J.L. Houghton. They applied for a patent in 1941.

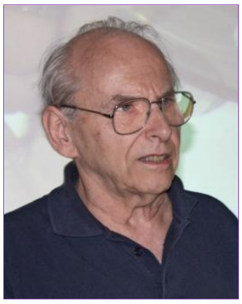
11.5 Bernhard Voldemar Schmidt (1879–1935): Optician and optical designer. Born in Estonia, at age 15 Schmidt lost his right hand when experimenting with gunpowder. He worked as a draftsman from 1899 to 1901 in Tallinn. After moving to Germany, Schmidt studied electrical and mechanical engineering at the Technical College ('Technikum') of Mittweida from 1901 to 1904. Then he founded an optical workshop in Mittweida, and won acclaim in 1906 for the production of a 41-cm f/2.26 paraboloidal telescope mirror for the Royal Astrophysical Observatory in Potsdam. In 1912, Schmidt refigured the 50-cm visual objective for Potsdam. His first contact with Hamburg Observatory came in 1916. For Hamburg he designed and constructed a 60-cm long-focus horizontal reflecting telescope with heliostat. Later he refigured the photographic objective of their 60-cm photographic refractor. By the end of his life, he held three patents and had built numerous optical systems for observatories at, e.g., Breslau (modern Wrocław), Vienna, Prague, Leiden and Leipzig. Today he is best-known for the invention of the aspheric corrector-plate 'Schmidt telescope' in 1929-1930.

11.6 Richard Reinhard Emil Schorr (1867–1951): Astronomer and observatory director. Schorr was Assistant Editor of the *Astronomische Nachrichten* from 1889 to 1891. Then he became assistant to the *Astronomisches Recheninstitut* in Berlin in 1891. Subsequently, he was Observer at Hamburg Observatory from 1892 to 1902, and then Director from 1902 until his retirement in 1941. Schorr planned and executed the move of the Observatory from central Hamburg to its present site at Bergedorf during the years 1900-1912. He specialized in positional astronomy. He was an occasional patron of Bernhard Schmidt from 1917, and regularly employed him from 1926 to 1935. In 1936, Schorr initiated plans for a large Schmidt telescope at Bergedorf, which was finally completed as an 80-cm instrument in 1955.

11.7 Hermann Slevogt (1909–1984): Optical engineer and physicist. Slevogt studied physics, mathematics, and astronomy in Bonn, graduating in 1932. He joined Carl Zeiss, Jena, in 1935, developing astronomical instruments. After resettlement in Heidenheim in 1945, he took part in building the West-German branch of Zeiss at Oberkochen. In 1952 he was appointed to the Chair of Technical Optics at the Technical University in Berlin, and served as Director of the Optical Institute. His areas of specialty were Seidel theory, diffraction theory, and the evaluation of image errors.

11.8 Arthur Arno Wachmann (1902–1990): Astronomer and Schmidt researcher. Wachmann studied at Kiel University, graduating in 1926. In 1927, he began working at Hamburg Observatory, first as Scientific Assistant, later as an Advisor, Supervisor, and finally Chief Observer, until his retirement in 1969. In 1962 he was made an Honorary Professor at Hamburg University. A dedicated observer and accomplished astrophotographer, Wachmann discovered four comets and a sub-class of T Tauri variable stars. Early on he recognized the importance of Bernhard Schmidt's work, and was one of the first people to take photographs through the original Schmidt corrector-plate telescope. He began his biographical work on Schmidt in the 1940s.

Wolfgang Busch (Ahrensburg, Germany) originally studied opto-mechanics and optical computation (the latter at the Hamburg-Bergedorf Observatory), beginning in 1948 after discharge from war service and completion of his secondary education. Later he altered his plans and devoted himself to the piano at the conservatory and to geography at the University of Hamburg. After taking his degrees, he taught gymnasium in Hamburg until his retirement in 1989. A lifelong amateur astronomer and telescope-maker, since the 1950s Busch has produced aspheric mirrors. In 1992, he devised special aspheric grinding techniques to build instrumentation for the Max Planck Institute of Flow Research in Göttingen. In the early 1970s, he invented the first modern oil-spaced apochromatic triplet telescope objectives for amateur astronomy, which he then described in print. More recently he has been involved in restoration projects. He has cleaned, measured and tested the 200-mm achromatic guiding telescope on the historic 1-meter Zeiss reflector at the Hamburg-Bergedorf Observatory; and he has developed specialized machining methods to restore worn Zeiss-B air-spaced apochromatic triplets—the most refined and delicate of all Zeiss' telescope objectives for amateur astronomy. He has published a detailed paper describing these methods. The largest of his restored Zeiss triplets (200-mm in diameter) was used as the collimator for the present study.



Dr Roger C. Ceragioli (Vancouver, Canada) obtained a Ph.D. in Classical Philology from Harvard University in 1992. Later he worked for a decade as an optician at the University of Arizona's Steward Observatory Mirror Lab, specializing in the production of aspheric mirrors and lenses in the half- to one-meter class. At present he designs lens systems for commercial production, and engages in historical research, serving on the History Committee of the Royal Astronomical Society of Canada. He is the author of several papers on the history and design of telescope optics, and is co-author (with Gregory Hallock Smith and Richard Berry) of *Telescopes, Eyepieces, and Astrographs: the Design, Analysis, and Performance of Modern Astronomical Optics*, (Willmann-Bell, 2012). He will soon complete a major study of the telescopes of William Herschel, and is producing the first English translation (from Latin) of Johannes Kepler's seminal book on the telescope, *Dioptrice* (1611). He and Walter Stephani are engaged in a long-term biographical study of Bernhard Schmidt.

Walter Stephani (Kiel, Germany) works in information technology for a company that specializes in the installation of air purification systems. During the 1980s and 1990s he published technical computer manuals. His academic training is in musicology and the history of music. Beginning in 1972 and mentored by Wolfgang Busch, Stephani learned optical fabrication and testing methods, which he used to build his own telescopes. Since 2004 he has devoted himself intensively to the historical study of Bernhard Schmidt, and has uncovered a vast array of new documentary sources, previously unavailable for scholarly study. Recently, he secured the donation of the priceless Wachmann-Schmidt archive of documents and photographs from Mr Erik Schmidt (Mallorca, Spain) to the University of Hamburg. Combined with the Bergedorf-Schmidt archive and artifacts, together they comprise the largest collection of materials in the world for the study of Bernhard Schmidt's life and scientific achievements.