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A simple null test for a Schmidt camera aspheric corrector

R. V. Willstrop *Institute of Astronomy, The Observatories, Madingley Road, Cambridge CB3 0HA*

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Summary. Existing accurate optical tests of the aspheric corrector of a Schmidt camera generally require auxiliary optics of good quality and large diameter. The test described here, which is believed to be original, requires only the spherical mirror which is to be used in the camera, and is accurate to the diffraction limit if the camera is not so fast that the profile of the corrector requires a term in r^6 in addition to the usual terms in r^2 and r^4. Another attractive feature of the test is that it may be carried out in yellow or red light although the corrector is to be figured for use in the blue or ultraviolet spectrum.

1 Introduction

During the later stages of manufacture, the aspheric face of a Schmidt camera corrector plate needs frequent testing, between short spells of figuring. Various test arrangements have been described by Lower (1937), Cox & Cox (1938, 1939), Waland (1938), DeVany (1939) and Hendrix & Christie (1939). Some of these papers have been republished (Ingalls 1953) together with a paper by Paul (1953). Strong (1939) describes two of the methods. Nearly all of the most sensitive of these tests require a first class telescope, to test the parallelism of light emerging from the camera from a small source at its focus, or a good flat mirror for an autocollimation test. The telescope or flat mirror must have an aperture which is more than half of that of the corrector to be tested, and preferably it should be at least as large as the corrector. There is one arrangement (Hendrix & Christie 1939, their Fig. 6C) which does not require any auxiliary optics except the spherical mirror, but this is not a null test and they recommend it only for cameras of $f/5$ and smaller aperture. Light from a pinhole placed close to the centre of curvature of the mirror passes twice through the corrector, which is placed very close to the mirror. The longitudinal position of the focus of the light that has fallen on a zone of radius r on the corrector, y_r, differs from the focus for light close to the axis, y_x, by $y_r - y_x = 2r^2/R$. This aberration is twice as large as that of a paraboloidal mirror with the same paraxial radius of curvature, R, when it is tested at its mean centre of curvature, and it would be difficult to detect and measure small errors by means of this test.

The new null test, which is shown in Figs 1 and 2 and described in detail in Section 3 below, also needs no other optics than the spherical mirror with which the corrector will be used. Some explanation of how this can be achieved seems desirable. A spherical mirror, used to focus parallel light, has considerable spherical aberration, and in the Schmidt camera this is corrected by an aspheric lens of suitable strength placed at the centre of curvature of the mirror. If the light source is not very distant the camera will no longer be well corrected for spherical aberration. Two factors contribute to this: first, the spherical aberration of the mirror alone becomes smaller as the light source is brought closer to it, and falls to zero when the source and focus are both at the centre of curvature; and second, with the source nearby and the corrector spaced apart from the mirror, the light that passes through any zone on the corrector falls on a zone of larger radius on the mirror, where the aberration to be corrected is greater. It has been found, by ray tracing, that if the distances of the conjugate foci from the mirror are near to the ratio 5 : 1, it is possible to find a position for the corrector, close to the short conjugate focus, such that the two factors noted above cancel each other, and there is no third-order spherical aberration. Furthermore, if the corrector profile is described by terms in r^2 and r^4 alone, there is one pair of distances of the conjugate foci from the mirror for which it is possible to find a position for the corrector along the axis where both the third- and the fifth-order spherical aberration are simultaneously reduced to the very small quantities required to balance the uncorrected seventh-order aberration. An important advantage of this test is that, by choosing the right pair of conjugate foci, and the right location of the corrector, this can be tested in monochromatic visible light such as Hg yellow light or He–Ne laser red light, and yet be properly figured for use in blue light or even in the ultraviolet spectrum. This feature, and the fact that the test needs no auxiliary optics which would have to be aligned with the spherical mirror and the corrector, makes this test useful for small cameras as well as large ones.

In Section 2 below it is shown that, although the radial profile of the corrector should (for mathematical exactness) contain terms in all even powers of r, practical considerations of the atmospheric seeing and of the finite resolution of photographic emulsions make it permissible to neglect the r^6 and higher terms without significantly affecting the image quality of slow and medium speed cameras. In marginal cases it may be permissible to omit the r^6 term provided that the strength of the r^4 term is increased slightly to effect a partial compensation. In all of these cases the test can be used as a null test; light from a small source on the axis of the corrector will be refocused to form a diffraction-limited image when the corrector has the proper figure. Detailed dimensions are given in Tables 2–4 of the arrangement of the test in these cases when one face of the corrector is plane. If the corrector is given a shallow meniscus form to minimize the surface brightness of ghost images the test is still a null test, but the separations of the mirror, corrector and foci must be changed.

The conditions under which it is permissible to use the test as a null test are established in Section 2, and it is shown that the null test is valid for almost all Schmidt cameras used for direct photography of the sky, though some spectrograph cameras are too fast to be tested in this way. The test is described in detail in Section 3 and its accuracy is discussed in Section 4.

The test may still be used, but no longer as a null test, if the optical performance of the camera would be noticeably degraded by omitting the r^6 term. This applies to three categories of camera:

(a) very fast cameras of the classical form, because the r^6 term is then not small enough to be neglected;

(b) aberration balanced cameras (Linfoot 1955) in which off-axis aberrations are reduced at the cost of slightly worse images on axis by deliberately including an r^6 term in the corrector profile and introducing an asphericity, proportional to r^4, on the mirror;

(c) cameras, such as the UK Schmidt Telescope, which are large enough to justify the expense of making an achromatic corrector, and which will then be practically free of the chromatic variation of spherical aberration which is the principal limitation of cameras of the classical form.

In tests of these cameras the longitudinal position of the focus of rays will vary slightly, depending on the fourth power of the radius of the zone on the corrector through which they passed. Optimum arrangements of the (non-null) test for these cameras have not been determined because very many different cases would have to be considered, and it would be preferable to examine each case individually.

2 The corrector profile

The equation of a paraboloid of focal length F with its pole at the origin ($x=0$, $r=0$) and its axis coincident with the x axis is $x=r^2/4F$ where x is the depth of the curve at a radius r from its axis. The equation of a spherical surface with the same axial curvature, i.e. $R=2F$, and with its centre of curvature at $x=R$, is $x'=R-(R^2-r^2)^{1/2}$ or $x'=2F-(4F^2-r^2)^{1/2}$. This equation may be expanded by the binomial theorem, and close to the origin all but the first few terms may be neglected:

$$x'=\frac{r^2}{4F}+\frac{r^4}{64F^3}+\frac{r^6}{512F^5}+\cdots. \tag{1}$$

The first term is the same as that of the paraboloid; the other terms, with their signs reversed, describe the asphericity of the surface of a paraboloidal mirror (Linfoot 1955).

The asphericity of a wavefront, previously plane, immediately after reflection in a spherical mirror is twice as great as the asphericity of the paraboloid, and for light of a chosen wavelength this can be corrected by a thin aspheric lens with refractive index n at that wavelength and with variations in its thickness increased by a further factor of $1/(n-1)$:

$$t_r=t_x+\frac{1}{(n-1)}\left\{\frac{\left(r^2-\frac{3}{2}r_0^2\right)r^2}{32F^3}+\frac{r^6}{256F^5}+\cdots\right\}, \tag{2}$$

where t_x is the axial thickness and r_0 is the maximum value of r. The constant 3/2 is normally chosen because (if we may for a moment neglect the comparatively small term in r^6) this makes the maximum convex slope, at $r=r_0/2$, equal to the maximum concave slope at r_0 and results in the minimum chromatic variation of spherical aberration, which is the principal aberration near the axis.

We now determine the conditions under which the r^6 term in the ideal corrector profile can be replaced by a slightly strengthened term in r^4 without affecting the optical performance of the finished camera significantly. Three criteria will be used in turn:

(a) the camera should still meet the Rayleigh criterion for diffraction-limited performance;

(b) the ray-theoretic image spread should be less than the best seeing experienced, other than on rare occasions, say 1 arcsec in diameter;

(c) the ray-theoretic image spread should be less than the spreading of light in a fine-grain photographic emulsion such as IIIa–J, say 10 μm in diameter.

2.1 DIFFRACTION-LIMITED PERFORMANCE

Let the term in r^6 in equation (2) be written as $x_6 = a_6 r^6$ and let it be replaced by a small change in the r^4 term $x_4 = a_6 r_0^2 r^4$ which will retain the original corrector thickness on axis and at the edge of the aperture, but leave it slightly too thick at intermediate radii. The error in thickness will be

$$\Delta t = x_4 - x_6 = a_6(r_0^2 r^4 - r^6). \tag{3}$$

By differentiating this equation we find

$$\frac{d\Delta t}{dr} = a_6(4r_0^2 r^3 - 6r^5). \tag{4}$$

The error in the thickness of the corrector is greatest at $r^2 = 2r_0^2/3$ and if this value is substituted in equation (3) we find that the maximum error in the thickness is

$$\Delta t_{\max} = a_6\left(r_0^2 \frac{4}{9} r_0^4 - \frac{8}{27} r_0^6\right) = \frac{4}{27} a_6 r_0^6. \tag{5}$$

To satisfy the Rayleigh criterion for nearly diffraction-limited performance the variation in optical path must be under $\pm\lambda/8$. If we allow the error to be $-\lambda/8$ at the centre and at the edge of the aperture it can reach $+\lambda/8$ at any intermediate radius. Then the condition to be

Table 1. The effect on Schmidt camera performance caused by omitting the term in r^6 from the corrector profile.
Column 1: Camera focal ratio.
Columns 2 and 3: Camera aperture in mm below which the r^6 term may be omitted without degrading the performance below the diffraction limit (column 2) or enlarging the image diameter above 1×10^{-2} mm (column 3).
Column 4: The image spread in arcsec, on axis at the optimum wavelength, if the r^6 term is omitted.

F/d	(diffraction)	(10 microns)	Image spread in arc sec
1.0	11.06 mm	39.4 mm	50.7
1.1	17.8	57.7	31.5
1.2	27.5	81.7	20.4
1.3	41.1	113	13.7
1.4	59.5	151	9.43
1.5	84.0	200	6.68
1.6	116	258	4.84
1.8	209	414	2.68
2.0	354	631	1.59
2.2	570	923	0.984
2.4	881	1308	0.637
2.6	1314	1802	0.427
2.8	1903	2423	0.295
3.0	2688	-	0.209

satisfied is:

$$\frac{\lambda}{4} \geqslant \frac{4}{27} \frac{r_0^6}{256F^5}. \tag{6}$$

Substituting $\lambda = 400$ nm and rearranging, we find the limiting value of the aperture $d(=2r_0)$ is:

$$d \leqslant 11.06 \left(\frac{F}{d}\right)^5 \text{ mm.} \tag{7}$$

This condition is satisfied by any Schmidt camera yet built of $F/3$ or slower speed; for $F/2$ cameras the aperture should be not more than 350 mm. The maximum apertures for other speeds are given in Table 1, column 2.

2.2 SEEING-LIMITED PERFORMANCE

Again let the term in r^6 be replaced by $x_4 = a_6 r_0^2 r^4$ and now also allow a small change in focus setting, or, which is equivalent, modify the term in r^2 by the addition of a small empirical correction 0.480475 $a_6 r_0^4 r^2$. Now the ray-theoretic errors of slope of the wave-front introduced by the omission of the r^6 term are:

$$\Delta S_6 = 4a_6 r_0^2 r^3 + 0.96095\, a_6 r_0^4 r - 6a_6 r^5 \tag{8}$$

$$= -1.039\, a_6 r_0^5 \qquad \text{at } r = r_0 \tag{9a}$$

$$= +1.039\, a_6 r_0^5 \qquad \text{at } r = 0.684\, r_0. \tag{9b}$$

Then the condition that must be satisfied if the ray-theoretic image spread is to be less than 1 arcsec in diameter (2.5×10^{-6} rad in radius) is:

$$\frac{1.039\, r_0^5}{256F^5} \leqslant 2.5 \times 10^{-6}. \tag{10}$$

Rearranging:

$$\left(\frac{F}{d}\right)^5 \geqslant \frac{1.039}{32 \times 256 \times 2.5 \times 10^{-6}} = 50.8 \tag{11}$$

i.e.

$$\frac{F}{d} \geqslant 2.2. \tag{12}$$

The Palomar and UK 48-inch Schmidt cameras meet this condition; the ray-theoretic image spreads for other focal ratios are given in Table 1, column 4.

2.3 PERFORMANCE LIMITED BY PHOTOGRAPHIC SPREAD

In this case the ray-theoretic image spread obtained in equation (10) above must be smaller than the radius of the image spread in the emulsion:

$$\frac{1.039\, r_0^5}{256\, F^5} \leqslant \frac{5 \times 10^{-3}}{F}. \tag{13}$$

Rearranging and evaluating, we find that the maximum aperture is

$$d \leqslant 39.4 \left(\frac{F}{d}\right)^4 \text{ mm.}$$

This condition is met even by the 18-inch, $f/2.0$, Schmidt camera of the Mount Wilson and Palomar Observatories, which is unusually fast for a camera of that aperture; the original Schmidt camera ($F = 625$ mm, $d = 360$ mm) is faster still, and just fails to meet the condition, but it was built before fine-grain emulsions of sufficient speed for astronomical photography, such as IIIa–J, were available. The maximum apertures for other focal ratios are given in Table 1, column 3.

3 The proposed test

Two alternative arrangements of the test are shown in Figs 1 and 2. The first is suitable for testing the correctors of most cameras, but may become impractical if the camera is faster than about $f/1.5$, if the corrector is relatively thick, or if it is to be tested at a wavelength only a little longer than that at which it will be used. The second test arrangement can then be used instead.

In the first arrangement light diverges from a pinhole or slit placed close to the aspheric face of the corrector, falls on the finished spherical mirror that will be used in the completed camera, and returns through the corrector to the longer conjugate focus of the mirror where the knife-edge, Ronchi grating or wavefront shearing interferometer is placed. In the second

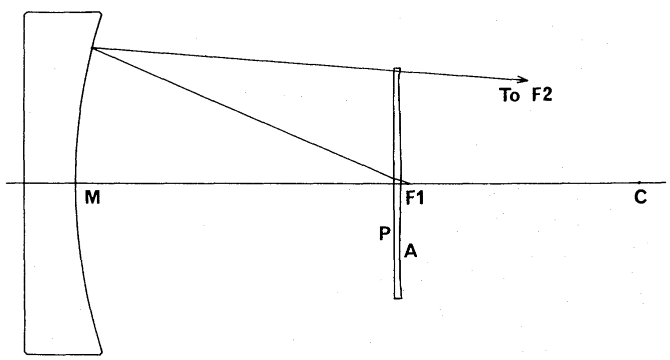

Figure 1. The null test for a Schmidt camera aspheric corrector, preferred form. M, spherical mirror; C, centre of curvature of mirror; P, plane face of corrector; A, aspheric face; F1, short conjugate focus and location of the monochromatic light source; F2, long conjugate focus and location of knife edge or other test device. One marginal ray is shown.

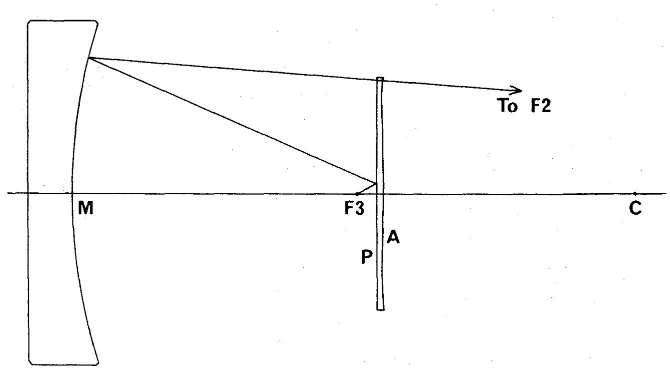

Figure 2. The alternative form of the null test for a Schmidt corrector. F3, short conjugate focus and location of the monochromatic light source; for other symbols see the caption to Fig. 1.

arrangement the light source is placed between the mirror and the corrector, and the light reflected from the plane face of the corrector is used in the test. In this case the housing of the light source must be made very small to minimize the obscuration it causes, and any irregular errors of figure near the centre of the plane face of the corrector affect the test approximately four times as much as in the first arrangement, which is therefore generally preferable. Because the spherical mirror must be finished for use in either form of this test, it can be aluminized, and the loss of light in the single air–glass reflection in the second arrangement is then acceptable. A small mask is required, at a suitable distance along the axis, to obstruct both the direct light from the source and the light reflected by the aspheric surface and refocused by the mirror.

The diameter of the patch on the mirror which should be illuminated is about 20 per cent larger than the clear aperture of the corrector, but this need cause no problem because it is normal practice to make the mirror 40 or 50 per cent larger than the corrector to reduce light losses off axis. Because the pinhole or slit is placed a little further than the focal length from the mirror, it needs to be illuminated by a lens of only slightly larger numerical aperture than the completed camera, NA 0.25 for cameras of $f/2.0$ and slower, or NA 0.50 for

Table 2. Dimensions in mm of the null test for a Schmidt camera corrector.
Corrector to be figured for use at λ = 400 mm.
Spherical mirror radius of curvature 2000 mm.
Camera nominal focal length 1000 mm.
Corrector plate material Schott UBK7. Thickness t_x = 10, 25 or 40 mm.
Test wavelength λ_t = 578.0 nm (Hg yellow) or 632.8 nm (He–Ne laser).
A-F1 = Separation of corrector (aspheric face) and shorter focus.
A-F2 = Separation of corrector (aspheric face) and longer focus.
P-F3 = Separation of corrector (plane face) and shorter focus.

λ_t :	578.0		578.0		578.0		632.8		632.8		632.8 nm	
t_x :	10.0		25.0		40.0		10.0		25.0		40.0 mm	
Aperture	Test arrangement 1 (twice through)											
	A-F1	A-F2	A-F1	A-F2	A-F1	A-F2	A-F1	A-F2	A-F1	A-F2	A-F1	A-F2
800	41.0	5323	10.4	5155	-19.1	5006	46.1	5368	15.0	5195	-14.9	5043
700	56.1	5373	25.0	5201	-5.1	5052	61.2	5419	29.7	5242	-0.7	5089
600	68.8	5419	37.6	5242	7.1	5090	73.9	5467	42.3	5284	11.6	5128
500	79.2	5459	48.0	5277	17.4	5122	84.3	5509	52.8	5320	21.9	5161
400	87.5	5494	56.3	5306	25.6	5149	92.6	5545	61.1	5350	30.2	5188
300	93.8	5521	62.7	5329	32.0	5170	98.9	5574	67.5	5375	36.6	5210
200	98.2	5542	67.2	5346	38.8	5135	103.3	5595	72.0	5392	41.1	5225
	Test arrangement 2 (once through)											
	P-F3	A-F2	P-F3	A-F2	P-F3	A-F2	P-F3	A-F2	P-F3	A-F2	P-F3	A-F2
800	67.0	5464	76.8	5466	86.6	5468	72.0	5515	81.9	5517	91.7	5519
700	82.0	5520	91.8	5522	101.6	5524	87.1	5573	97.0	5575	106.8	5577
600	94.8	5569	104.6	5570	114.5	5572	100.0	5623	109.9	5625	119.7	5627
500	105.6	5610	115.4	5612	125.2	5614	110.9	5667	120.7	5668	130.6	5670
400	114.3	5645	124.2	5647	134.0	5649	119.7	5702	129.5	5704	139.4	5706
300	121.1	5672	130.9	5674	140.7	5676	126.5	5730	136.4	5732	146.2	5734
200	125.9	5691	135.7	5693	145.6	5695	131.3	5751	141.2	5753	151.1	5754

$f/1.0$ to $f/2.0$. The longer conjugate focus of the mirror is separated from the corrector by approximately five times the focal length of the completed camera, so that the corrector of an $f/2$ camera under test will appear nearly as large as an $f/5$ sphere tested at centre of curvature.

The optimum spacings between the light source, the corrector and the long conjugate focus given in Tables 2–4 have been determined using ray tracing programs (Willstrop, unpublished) based on the algebraic method of Smith (1923). The spacing between the mirror and the plane face of the corrector is in the majority of cases between 1.05 and 1.20 times the focal length of the camera and as it is determined by the other data it has been omitted to reduce the material tabulated. The cases considered were: radius of curvature of the camera mirror, 2 m (nominal focal length, 1 m); aperture of the corrector plate, from 200 to 800 mm by increments of 100 mm; axial thickness of the corrector, 10, 25 or 40 mm; corrector material, Schott UBK7 glass; corrector to be figured for minimum spherical aberration at 400, 440 or 500 nm; and the test to be carried out using either Hg yellow light (mean wavelength 578 nm) or a He–Ne laser (632.8 nm). In every case the corrector was assumed to be figured to give the minimum chromatic variation of spherical aberration, with minimum thickness at 0.866 of the clear aperture, and the rear surface was assumed to be plane. The coefficients of r^2 and r^4 in the profiles of the correctors are given in Table 5; the coefficient of r^6 was zero in every case. The refractive indices of UBK7 for the wavelengths noted above are given in Table 6. Test data for cameras of other focal lengths may be

Table 3. Dimensions in mm of the null test for a Schmidt camera corrector.
Corrector to be figured for use at $\lambda = 440$ nm.
For other data see the heading of Table 2.

λ_t :	578.0		578.0		578.0		632.8		632.8		632.8	nm
t_x :	10.0		25.0		40.0		10.0		25.0		40.0	mm
Aperture					Test arrangement 1 (twice through)							
	A-F1	A-F2	A-F1	A-F2	A-F1	A-F2	A-F1	A-F2	A-F1	A-F2	A-F1	A-F2
800	30.8	5235	1.0	5076	-27.8	4935	35.6	5277	5.4	5114	-23.7	4970
700	45.6	5282	15.4	5121	-14.0	4979	50.5	5325	19.9	5160	-9.8	5015
600	58.2	5324	27.8	5159	-2.0	5016	63.2	5369	32.4	5199	2.3	5052
500	68.6	5361	38.1	5192	8.1	5047	73.6	5407	42.7	5233	12.5	5084
400	76.9	5392	46.4	5219	16.3	5073	81.9	5440	51.1	5261	20.7	5110
300	83.2	5418	52.8	5241	22.7	5092	88.2	5467	57.4	5284	27.1	5130
200	87.6	5436	57.2	5257	27.1	5107	92.6	5486	61.9	5300	31.6	5145
					Test arrangement 2 (once through)							
	P-F3	A-F2	P-F3	A-F2	P-F3	A-F2	P-F3	A-F2	P-F3	A-F2	P-F3	A-F2
800	56.6	5363	66.4	5365	76.2	5367	61.5	5410	71.3	5412	81.1	5414
700	71.4	5415	81.2	5417	91.0	5419	76.4	5464	86.2	5466	96.0	5468
600	84.1	5460	93.9	5462	103.7	5464	89.1	5511	98.9	5513	108.8	5515
500	94.7	5499	104.5	5501	114.3	5503	99.8	5551	109.6	5553	119.5	5555
400	103.3	5531	113.1	5533	123.0	5535	108.5	5584	118.3	5586	128.2	5588
300	110.0	5556	119.8	5558	129.6	5560	115.2	5610	125.0	5612	134.9	5614
200	114.7	5574	124.5	5576	134.4	5578	119.9	5629	129.8	5631	139.6	5633

Table 4. Dimensions in nm of the null test for a Schmidt camera corrector. Corrector to be figured for use at $\lambda = 500$ nm. For other data see the heading of Table 2.

λ_t :	578.0		578.0		578.0		632.8		632.8		632.8 nm	
t_x :	10.0		25.0		40.0		10.0		25.0		40.0 mm	
Aperture	Test arrangement 1 (twice through)											
	A-F1	A-F2	A-F1	A-F2	A-F1	A-F2	A-F1	A-F2	A-F1	A-F2	A-F1	A-F2
800	20.2	5145	-8.8	4996	-36.8	4861	24.8	5185	-4.5	5032	-32.9	4895
700	34.9	5189	5.4	5038	-23.3	4905	39.6	5230	9.8	5076	-19.3	4939
600	47.3	5229	17.6	5075	-11.5	4941	52.1	5271	22.1	5113	-7.3	4975
500	57.7	5263	27.9	5106	-1.5	4971	62.5	5306	32.4	5145	2.7	5008
400	65.9	5292	36.1	5132	6.6	4995	70.7	5336	40.7	5171	10.9	5031
300	72.2	5315	42.5	5153	12.9	5014	77.0	5360	47.0	5192	17.2	5050
200	76.7	5332	46.9	5167	17.4	5027	81.5	5378	51.5	5208	21.7	5064
	Test arrangement 2 (once through)											
	P-F3	A-F2	P-F3	A-F2	P-F3	A-F2	P-F3	A-F2	P-F3	A-F2	P-F3	A-F2
800	45.8	5262	55.6	5264	65.4	5266	50.5	5306	60.3	5308	70.2	5310
700	60.5	5310	70.3	5312	80.1	5314	65.2	5356	75.1	5358	84.9	5360
600	73.0	5353	82.8	5355	92.6	5357	77.8	5400	87.7	5402	97.5	5404
500	83.5	5389	93.3	5391	103.1	5393	88.4	5437	98.2	5439	108.1	5441
400	92.0	5419	101.8	5421	111.6	5422	96.9	5468	106.8	5470	116.6	5472
300	98.5	5442	108.4	5444	118.2	5446	103.6	5492	113.4	5494	123.2	5496
200	103.2	5459	113.0	5461	122.9	5462	108.3	5509	118.1	5511	127.9	5513

obtained by scaling the data in Tables 2–4, and interpolating for other focal ratios, axial thickness as a fraction of the focal length, and wavelength of minimum spherical aberration.

A negative value of A-F1 in Tables 2–4 indicates that the optimum dimensions for the first form of the test are impracticable; the short focus lies within the material of the corrector. If this focus is moved a few millimetres to an accessible position just outside the corrector a significant amount of third-order spherical aberration will be introduced, as

Table 5. Coefficients of the r^2 and r^4 terms in the profiles of the correctors.

Wavelength:	400 nm		440 nm		500 nm	
Aperture	$10^{-5}r^2$	$10^{-11}r^4$	$10^{-5}r^2$	$10^{-11}r^4$	$10^{-5}r^2$	$10^{-11}r^4$
800	-1.48628	6.19322	-1.49920	6.24702	-1.51313	6.30509
700	-1.12420	6.11844	-1.13396	6.17159	-1.14450	6.22896
600	-0.81740	6.05518	-0.82450	6.10778	-0.83217	6.16456
500	-0.56272	6.00273	-0.56761	6.05487	-0.57289	6.11116
400	-0.35761	5.96053	-0.36072	6.01231	-0.36407	6.06820
300	-0.20006	5.92815	-0.20180	5.97964	-0.20368	6.03523
200	-0.08857	5.90524	-0.08934	5.95654	-0.09017	6.01191

Table 6. Refractive indices of Schott UBK7 glass at certain wavelengths.

Wavelength	Refractive index
400 nm	1.53083
440	1.52625
500	1.52141
578.0	1.51721
632.8	1.51509

discussed in Section 4. However, if the distance of the longer focus from the corrector, A-F2, is reduced by an appropriate amount the third-order aberration can be reduced to the very small amount required to balance the fifth-order aberration.

It has been verified that the test can be carried out on a corrector with a weakly spherical back, instead of plane, though the dimensions of the test arrangement must be changed. The large range of possible shapes of correctors makes it impractical to give here the data for testing any other than those with plane rear surfaces; in any case a serious optician wishing to make a corrector with an overall meniscus form to reduce the surface brightness of ghost images, for example, may be expected to have access to a comprehensive set of ray tracing subroutines and should have no difficulty in determining the optimum arrangement for the test.

4 Accuracy of the test

The effect of neglecting the term in r^6 in the ideal profile of a Schmidt camera corrector is discussed in Section 2 above. In Fig. 3(a) the lateral aberrations of nine rays at focus are plotted as a function of the initial ray height above the axis, for an $f/2$ camera of nominal focal length 1 m (hereinafter described by its aperture and focal length in millimetres, as 500/1000), receiving parallel light. The greatest lateral aberration is 5×10^{-3} mm,

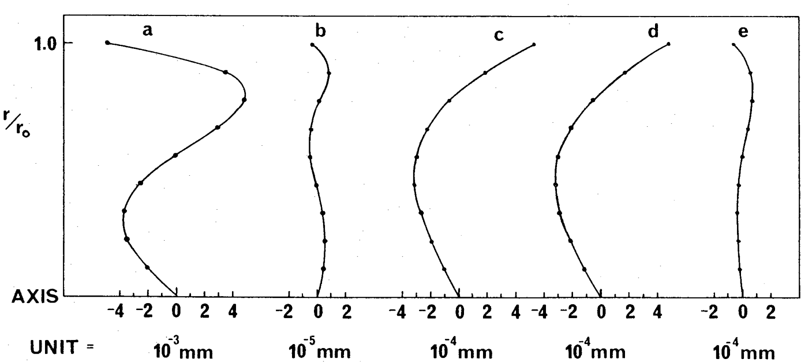

Figure 3. Lateral ray aberrations at focus for a Schmidt camera of 1 m focal length and 500 mm aperture as a function of the height of the ray above the axis when passing through the corrector: (a) in the completed camera, on the axis of the corrector, and at the optimum wavelength, when the r^6 term is omitted from the corrector profile, unit $= 10^{-3}$ mm; (b) in the null test, using the optimum spacings given in Tables 2–4, unit $= 10^{-5}$ mm; (c) in the null test, with F1 or F3 displaced by 1 mm from the optimum position and with F2 at the correct position, unit $= 10^{-4}$ mm; (d) in the null test, with F2 displaced by 50 mm from the optimum position and with F1 or F3 at the correct position, unit $= 10^{-4}$ mm; (e) in the null test for a corrector 40 mm thick, to be figured for use at 500 nm and the test to be carried out using Hg yellow light ($\lambda = 578$ nm), with F1 removed from an inaccessible position 1.5 mm inside the corrector to 1.6 mm outside it, and F2 moved 100 mm towards the corrector to correct the third-order spherical aberration, unit $= 10^{-4}$ mm.

giving a performance which might just be considered satisfactory for photography on fine-grain emulsions. The aberration is predominantly fifth-order spherical aberration, balanced by an appropriate amount of third-order aberration, and with small amounts of the seventh and higher orders; the image spread in cameras of the same focal length and of other apertures therefore varies slightly more than in proportion to the fifth power of the aperture.

In the following discussion of the residual aberrations in this test it will be assumed that the light source is placed at the focus further from the corrector, and the image spreads will be assessed at the nearer focus. Because the numerical aperture at the nearer focus is almost the same as at the focus of the completed camera the image spreads there in the test are more nearly comparable with the image spreads that will be obtained when the camera is in use. If the test for the corrector of the 500/1000 camera is set up using the dimensions given in Tables 2, 3 or 4 (depending whether the corrector is to be figured for use at 400, 440 or 500 nm respectively) the lateral ray aberrations at the shorter focus will be as shown in Fig. 3(b) if the corrector profile is as given in Table 5. Note the change of scale from Fig. 3(a); the greatest aberration is smaller than 1×10^{-5} mm, or $\sim\lambda/40$. The test itself is therefore well within the Rayleigh criterion, and its accuracy will be determined by the diffraction of light. The residual aberration is predominantly seventh-order spherical aberration (balanced by appropriate amounts of the third and fifth order); for slower cameras it is utterly negligible, and faster cameras of this focal length will not give a first class performance because of the chromatic variation of spherical aberration and through the neglect of the r^6 term in the corrector profile.

Small displacements of both the light source and the knife edge from their ideal positions cannot be avoided in practice, and these result mainly in third-order spherical aberration, causing the corrector to be made slightly too strong or too weak. Alternatively, the error can be regarded as figuring the corrector for a wavelength slightly different from that which was intended. Fig. 3(c) shows the change in the ray aberrations that result at the shorter focus when this is displaced by 1 mm from its proper distance from the corrector, and the long focus is kept in the proper position by a small axial movement of the mirror. The maximum change in the aberration of any ray in the test for the 500/1000 corrector is under 5×10^{-4} mm. Fig. 3(d) shows the change in the aberration that results when the shorter focus is properly positioned and the mirror is moved to displace the longer focus 50 mm from its proper position. Again the maximum aberration is under 5×10^{-4} mm. These displacements, of 1 and 50 mm at the short and long foci respectively, leave the accuracy of the test itself very close to the limits set by the diffraction of light in the case of the 500/1000 camera. The residual aberrations in the test are proportional to the displacements, if these are small, and they increase in proportion to the third power of the aperture of the camera. Cameras of this focal length and faster than $f/2$ have images that are larger than is desirable because of the chromatic variation of spherical aberration, while for slower cameras the test is well within the diffraction limit.

If the shorter focus is inaccessible a small distance within the thickness of the corrector it may be satisfactory to reposition it just outside, and in order to correct the third-order aberration which this movement introduces the longer focus should be moved nearer to the corrector. In Fig. 3(e) the lateral ray aberrations are shown for the particular case of the 500/1000 camera with a corrector 40 mm thick, figured for 500 nm and tested using Hg yellow light 578 nm, with A-F1 changed from -1.5 to $+1.6$ mm and A-F2 reduced by 100 mm to 4871 mm. The test is again diffraction limited. The aberration remaining is of the same type as that in the completed camera resulting from the omission of the r^6 term in the corrector profile, but in this example it is only one hundredth as large.

Cameras of very short focal length can be made substantially faster before the image spread becomes unacceptable. In the following the focal length is assumed to be 100 mm; few cameras are likely to be made smaller than this. At $f/1.25$ (aperture 80 mm) the image spread on axis at the optimum wavelength is $\pm 5.6 \times 10^{-3}$ mm when the camera is in use, if the r^6 term is omitted, and in the optimum test arrangement the maximum lateral aberration of any ray is $\pm 2.6 \times 10^{-5}$ mm at the shorter focus. The foci must be positioned more accurately in this case because of the small scale of the test; ray tracing shows that displacements of 0.1 mm of the short focus and of 5 mm of the longer focus result in lateral aberrations at the shorter focus of 2.3×10^{-4} and 2.0×10^{-4} mm respectively. Because the numerical aperture at the focus is now greater than in the test of the 500/1000 camera this test is also close to the diffraction limit. However, displacements of 1 mm and 50 mm of the two foci result in aberrations only half as great as those resulting from omitting the r^6 term from the corrector profile.

Provided that reasonable care is taken in setting up this test of a Schmidt camera corrector the results will be a reliable guide to the optician during figuring.

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