

Novel technique for the design of ultra-fast, high-resolution, broad-spectrum, wide-angle catadioptric lenses

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Abstract. A new optical design technique for catadioptric imaging optics is described, that permits near-zero values for the classical Seidel aberrations at relative apertures faster than $f/1$, with field angles over 3 deg arc, $\sim 10^6$ resolved pixels, a 600-nm bandwidth in the visible and near infrared and zero vignetting. Performance is limited only by high-order aberrations. The principle is that of combining the concentricities of a spherical concentric catoptric and a spherical concentric catadioptric, by optical superposition of the centers of curvature. The only full-aperture component is a spherical mirror; all other surfaces are spherical, except for an optional small weak zonal corrector. The new design approach is suited to aperture diameters of ~ 100 mm to >1 m when used with appropriate electronic detectors. Variants are possible for any segment of the electromagnetic spectrum for which there are suitable refractive and reflective media. In general, a large improvement in data acquisition rate is possible compared to that of existing designs. © 1999 Society of Photo-Optical Instrumentation Engineers. [S0091-3286(99)00610-8]

Subject terms: optical design; fast optics; catadioptrics; spherical-aberration correction; concentric optics; optical relay; near infrared; thermal infrared.

Paper 980281 received July 27, 1998; revised manuscript received Apr. 12, 1999; accepted for publication Apr. 19, 1999.

1 Introduction

It has been found possible to construct a class of imaging optic with numerical apertures (NA) >0.5 and linear resolution comparable with CCD pixel dimensions, while maintaining ~ 3 -deg field angles and 600-nm spectral bandwidths. Entrance pupil diameters (EPDs) can be up to ~ 1 m. This has been achieved with only a single full-diameter component, a spherical mirror, all other major components having subdiameter spherical surfaces in a concentric format.

The use of concentric spherical optical systems to reduce or eliminate off-axis aberrations has been understood for many decades. Schmidt¹ was the first to introduce a practical coma-free system for use in cameras of large EPD, and Maksutov² and Bouwers³ devised the first spherical surface correctors for similar systems. All these camera types require full-aperture-diameter spherical-aberration correctors, the Schmidt aspheric thin plate offering some fabrication difficulties, and the Maksutov and Bouwers thick menisci requiring massive homogeneous glass blanks. Derivatives of these systems can achieve speeds of $f/1$ or faster only by introducing significant complexity into the full-aperture-diameter refractive components and are generally bandpass-limited to about 300 nm in the visible and near infrared (NIR).

Speeds of the order of $f/1$ (NA ~ 0.5) are preferred for low-light-level imaging systems, but it is the combination of speed with adequate field angle, high angular resolution, and high spectral bandwidth that characterizes a high-

quality optic. Other desirable features are an external focal surface, low distortion and low vignetting, compact format, and conventional optoengineering. The new design method described in this paper achieves all of these preferred characteristics.

2 Optical Principle

The basic principle is shown in Fig. 1. A concentric spherical Cassegrain mirror system* with a stop at the center of curvature (CoC) generates an image of the object at the position *A*. This image is uniformly defective with spherical aberration and also is concentrically spherical. At location *A* is placed a field lens, which has as its primary function the reimagining of the original CoC to position *B*. At *B* is placed the entrance pupil of a camera (which may also be called a focal reducer), and just before this camera is placed a Bouwers-type concentric spherical meniscus with its CoC coincident with *B*.

It is apparent that the concentric meniscus can be so specified as to remove the third-order spherical aberration of the Cassegrain primary imaging module. The camera module (focal reducer) can then be designed to reimage the object onto the detector, with the added requirement that

*The term "Cassegrain" is used in this paper to describe the geometrical format of concave primary and convex secondary mirrors in an axial configuration, but here they are spherical and concentric. Equally well, a single spherical mirror in Newtonian format could apply, but, for the purpose of diagrammatic simplicity, an axial system of concentric spherical mirrors is assumed to create the first image.

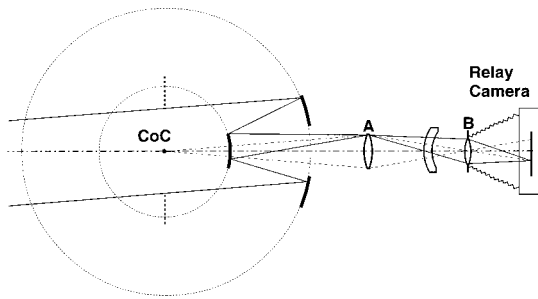


Fig. 1 The optical principle of the KiwiStar design system. A concentric spherical Cassegrain system, which has a stop at the center of curvature (CoC), generates an image at location A, at which point is placed a field lens that also reimages the CoC to location B. At B is placed the pupil of a relay camera. A concentric meniscus with its CoC at B can correct the spherical aberration of the Cassegrain system, and is much smaller than if it were related to the first CoC.

the camera lens should remove the longitudinal chromatic aberration of the concentric spherical meniscus, since the latter acts as a weak negative singlet lens. This arrangement is valid for any relay camera capable of achieving the required output resolution and spectral bandwidth of the system design specification.

The advantages offered by this combined system include:

1. The entrance pupil diameter is not limited by the availability of homogeneous refractive materials. The correction for spherical aberration of the primary mirror system has been allocated to a relatively small meniscus lens close to the focal reducing camera module, while the entrance pupil diameter is related only to the catoptric spherical mirror system. The only full- (or, rather, over-) size element of the entire system is the spherical primary mirror, a relatively low-cost item
2. The catoptric system's former aperture stop (at the entrance pupil) can be eliminated—this function has been transferred to the aperture stop of the focal reducing camera, the new marginal ray delimiter. Consequently, the system length has been reduced by a distance equal to the separation of entrance pupil and secondary mirror, enabling more compact instrument packages. There are obvious further opportunities for folding the system if compactness is essential.

The focal reducing camera module must now be specified. Because the intermediate image is of uniform quality, independent of field angle, it is relevant to maintain this property and choose a system with similar characteristics, such as a spherically concentric catadioptric. Several appropriate systems exist, ranging from the original Schmidt design to complex Maksutov-Schmidt systems, such as derivatives of the Baker⁴ camera. Apart from the pure Schmidt, the generic fast concentric camera includes a Bouwers or Maksutov meniscus corrector, and it is an immediately obvious operation to merge this with the meniscus, previously described, that corrected the primary system's spherical aberration.

Figure 2 illustrates an example of a complete system, in which a very fast variant of the Hawkins-Linfoot camera⁵

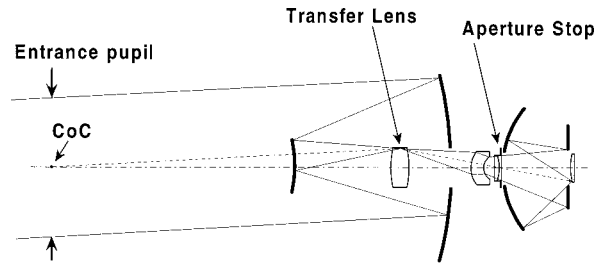


Fig. 2 Generic layout of a dual-concentric system, in which a folded, finite-conjugate variant of the Hawkins-Linfoot camera⁵ is used as a focal reducer, while retaining system concentricity.

has been inserted into the system, modified for the finite conjugate imaging required, and folded to externalize the focal surface. The concentric meniscus corrects the low-order spherical aberration of both primary and secondary mirrors and focal reducer mirrors, and the positive-error chromatic doublet at the aperture stop compensates the negative-error axial color of the meniscus, while simultaneously correcting the zonal error by means of a weak aspheric rear surface, located precisely at the aperture stop. For more demanding specifications, much-improved correction of the higher-order aberrations is possible by apochromatizing the system as described below.

There remains to remove one Seidel aberration, inherent in all concentric optics—field curvature. Semiconductor detectors, such as CCDs, are inherently planar, so it is necessary to flatten the field, either by inserting a simple Petzval lens, or by coupling *via* a bonded fiber plate with a convex front surface coincident with the image surface. At $f/1$ and faster, the marginal ray incidence is so large that a Petzval lens has to be in contact with the silicon surface structure in order to avoid introducing significant coma and astigmatism. The fiber-plate option is inherently superior in that respect but may have a fill factor of the order of only 70% because of the fiber cladding. Also, to avoid contamination of the image surface, it is advisable to bond to the fiber plate surface a concentric spherical cap of sufficient thickness to blur to insignificance the obscuration caused by dust particles. The thickness of this cap can be incorporated into the spherical-aberration control of the design. Similarly, the window of a cryostat should be designed concentric with the other relay components.

The only nonconcentric components in the system are the field lens (which optically transfers the pupil and the CoC of the primary system to that of the focal reducer), the chromatic corrector, which is located at the aperture stop, and the Petzval-type field flattener (if this is used). The effect of these is to generate high-order aberrations that are a function of NA and obliquity, and that constrain the usable field angle to a limit set by the resolution specification.

The result of this catoptric catadioptric combination is an unusually high product of field angle \times NA \times resolution \times spectral bandwidth, in imaging optics that are scalable over a large range of EPDs. This new design method has the name KiwiStar, and is the subject of world patents (including United States Patent No. 5,734,496).

3 Aberration Control

As in most catadioptric systems, the focusing power resides in the mirror components, so chromatic error is small compared to that of refractive-power lenses. In KiwiStar designs, the chromatic aberration is caused almost entirely by the concentric meniscus acting as a weak negative-power lens, so the color error is relatively simple to control with the chromatic corrector at the aperture stop. However, this zero-power corrector intercepts a diverging beam with an obliquity that increases to the limits of the focal-reducer field angle, thus introducing a noticeable amount of coma into the system.

An empirical technique for compensating this is to introduce equal and opposite coma at some other suitable place in the optical train. For example during the optimization process, it has been found effective to disturb the concentricity of the system by modifying the focal length of the field lens so that the image of the aperture stop is displaced from the "correct" position at the CoC of the catoptric primary module. This is, however, a crude process, albeit simple, and is appropriate only to smaller-scale KiwiStars. A superior solution is to introduce an extra component into the system by designing the color compensator as an apochromatizing triplet. The additional degrees of freedom thus created allow excellent high-order aberration control. Two computed examples are presented below.

It might be thought that the operation of the aspheric zonal corrector could be degraded by obliquity effects at the field limits, but the asphere is so weak—only a few micrometers peak-to-valley height—that no significant effect has been observed.

Another component that can introduce unwanted aberrations is the field lens. It is unusual for a field lens to be the source of aberrations, but when included in the high-level aberration correction of KiwiStar lenses, even this component has to be carefully detailed. In the interest of good practice, early development design studies had employed a split field lens so as to place the intermediate image in an air space, but the extra surfaces add to the fabrication cost and the gain in aberration control over a thick singlet was found to be insignificant. The examples given in this paper generally place the intermediate image within the mass of a thick singlet, care being taken to choose a glass of reliable bubble-free homogeneity—BK 7 from the Schott catalog being typical. An exception has been found in the most highly corrected variants of the KiwiStar systems, for which the field lens is best designed as a doublet, so as to remove the small amount of lateral chromatic aberration inherent in a singlet lens. In all cases, the thickness, positioning, and surface radii of the field lens have to be optimized for the best system performance.

An "aberration" that must be considered in practical realization is the attenuation of the system transmission due to the <100% reflectance of mirrors and transmittance of lenses. In the twice folded KiwiStar represented in Fig. 2, with four mirrors, seven air-glass surfaces, and a 23% central obstruction, the system transmittance could be as low as 0.36 (viz., 85% reflectance for aluminum, 2% residual reflectance for air-glass over a 480- to 1100-nm spectral passband, and 77% pupil working area) or as high as 0.64 (98% for enhanced silver over 480 to 1100 nm). In other formats, higher transmittance values can be achieved—e.g.,

a Newtonian-format catoptric module, with an 88% pupil utilization, followed by an unfolded catadioptric (internal focus), would have a transmittance of 0.72 (enhanced silver), or 0.77 if the air-glass coatings could achieve 1% residual reflectance over the 600-nm-wide spectral passband.

4 Examples

A prototype unit was constructed in 1995 to test the principle and gain experience. It was based on the hardware of a Meade[†] 10-in. Schmidt-Cassegrain astronomical telescope, which was optically modified but which retained the original spherical primary mirror and tube structure. The Meade corrector was replaced with an optical-quality plane-parallel window to support the spherical secondary mirror, and an additional focal reducer module (based on the Hawkins-Linfoot camera, as discussed above) was attached to the rear mirror cell. Figure 2 is representative of the layout. The specification of this instrument was: $F = 180$ mm, $f/0.9$, 400- to 1100-nm passband, angular field 2.2×2.9 deg on a 2/3-in. (6.9×9 -mm) CCD chip. Performance, demonstrated in the CCD video output, closely matched prediction, and resulted in pixel-limited resolution over 75% of the 756×581 pixel array. The optical prescription is listed in Table 1, and the computed performance is illustrated in the form of ray-intercept point spread function[‡] (PSF) histograms in Fig. 3. Diffraction effects are ignored.

This prototype was exhibited at the 1995 SPIE Symposium and Exhibition at San Diego, and attracted the notice of a physics group at Los Alamos National Laboratory (LANL), who were seeking a suitable lens for high-NA imaging of a scintillator at standoff distances in the range 1 to 10 m. A second instrument (the BN-2 KiwiStar) was constructed for this group, and was delivered in February 1997, with the specification: 3.5-m standoff distance, 400 mm, $f/1.1$, 8.33:1 conjugate ratio, 380- to 600-nm passband. This instrument is illustrated in Fig. 4. The scintillator diameter of 150 mm was to be imaged on to the fiber faceplate of an image intensifier of 18-mm diam, with tapered fiber plugs allowing the use of 25- and 40-mm intensifiers where required (trading off speed for resolution at the final electronic detector). The resolution at the edge of the scintillator was to be 5 cycles/mm at 50% MTF (42 cycles/mm at the image). The optical prescription is listed in Table 2, and the computed performance is illustrated in Fig. 5.

Testing was carried out by reverse projection of a metal-on-glass multiple starburst pattern, contacted to the 40-mm-diam surface of a tapered fiber plug located at the focal surface, and focused on the future location of the scintillator target. The fiber plug had a correctly radiused 18-mm-

[†]Meade Instrument Corporation, 6001 Oak Canyon, Irvine, CA 92620, USA.

[‡]Each of the PSF histograms in this paper was generated by integrating 10^6 pupil-filling ray intercepts at the focal surface. Obscurations and vignetting are allowed for, but diffraction is ignored. The fine structure is sometimes a function of the line-spectrum input to the computation. The spectrum lines chosen are all those in the Schott catalog that lie within the system passband, and they have identical weights. All the histograms are normalized to the same arbitrary height.

Table 1 Optical prescription of the KiwiStar prototype. To minimize fabrication costs, all radii, except that of the Meade primary mirror, were chosen from the tool stock⁶ of the Industrial Research Limited optical workshop. Glasses were selected from conveniently sized stock blanks. The performance is illustrated in Fig. 3. The aspheric coefficients in this and subsequent tables refer to the equation for the sag of the surface of curvature c and conic constant k at radius r : $\text{stage} = cr^2/[1 - (1+k)c^2r^2]^{1/2} + A_2r^2 + A_4r^4 + A_6r^6 + A_8r^8$. Aspheric coefficients of surface 11: $A_2 = -5.55\text{E}-05$, $A_4 = +1.35\text{E}-07$, $A_6 = -6.17\text{E}-11$, $A_8 = -2.28\text{E}-14$.

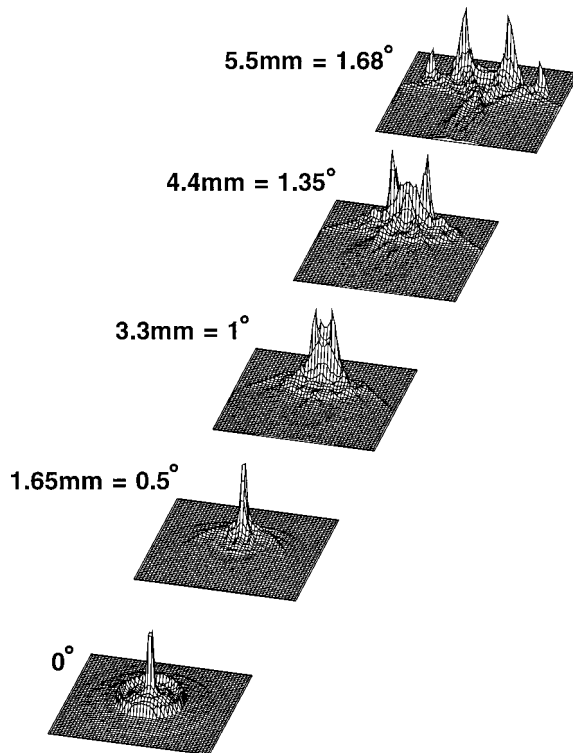
Surface	Glass	Spacing (mm)	Curvature (mm ⁻¹)	Radius (mm)	Mirror or lens	Inner diam (mm)	Outer diam (mm)
1 Sph. prim.			-0.00098668	-1013.50	M	97	265
2 Sph. sec.		-356.90	-0.00152300	-656.60	M		100
3		262.00	0.00634040	157.70	L		58
4 Field	SK 11	18.00	-0.00257140	-388.90	L		58
5		166.00	0.01618909	61.77	L		55
6 Meniscus	SK 4	19.82	0.02384359	41.94	L		55
7		12.79	0	Flat	L		50
8 Filter	BK 7	3.00	0	Flat	L		50
9		20.98	0	Flat	L		52
10 Doublet	F 4	5.17	-0.00747940	-133.70	L		52
11 Ap. stop	SK 4	4.83	Aspheric 0	Flat	L		52
12 Fold		65.00	0	Flat	M	38	100
13 Relay		-82.20	0.00678196	147.45	M	58	140
14		98.79	0.0335354	29.82	L		12
15 Petzval	SF 2	1.00	0	Flat	L		12

diam image surface, so the full field of the instrument was checked for resolution and MTF contrast. The LANL team has accepted the system as meeting the design specification.

It is a measure of the ease of manufacture of these two existing models that all the required metal and optical components were fabricated to unexceptional engineering tolerances, and with standard techniques, in the Industrial Research Limited mechanical (Auckland) and optical (Wellington) workshops. Tilt and decenter errors were reduced to negligible levels by the use of precision coaxial assembly jigs. The aspherical zonal trimmer surfaces were templated in the design stage as a pattern of interference fringes, as required to be viewed in a Fizeau interferometer. A petal lap rapidly removed the few micrometers maximum depth of glass.

A series of computed designs has now been examined with EPDs ranging from 100 mm to 2 m. The smaller variants are suited for use with 1/3- and 1/4-in. video standard CCD imagers—at this reduced scale, the greater field angles associated with the larger video standards involve significantly increased central obscurations in the catoptric system.

The first design study was an apochromatized version of the prototype. This was computed for the purpose of imaging with 2/3 in. CCD devices that are constructed with the smallest pixels presently manufactured (of the order of 6- μm side dimension). By replacing the doublet chromatic corrector with a triplet of Schott KzF N2 and FK 51 glasses, much greater control of the residual high-order aberrations is possible. Some minor adjustments of the field lens power and of the field flattener were also necessary, and the resulting prescription is given in Table 3. The performance is shown in Fig. 6, and it can be seen that the blur dimension has been significantly reduced for all field



Histogram dimensions: 20X20 μm

Fig. 3 Performance of the KiwiStar prototype, as initially constructed to match CCD pixels 10 μm square. The geometrical speed of $f/0.9$ is degraded by the central obstructions and by aluminizing losses to $t/1.2$. Passband is 435 to 1014 nm. The structures evident in this and subsequent computed PSF histograms are due to the line-spectrum input wavelengths of $g, F, e, d, C, r, s,$ and t , as well as to the usual cusps and loops of high-order aberrations.

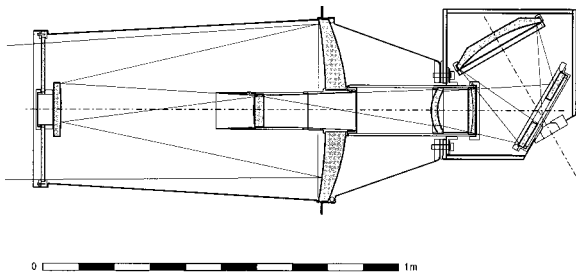


Fig. 4 The 3.5-m-range KiwiStar delivered to LANL in February 1997. It is a 436-mm EFL, 8.33 : 1-conjugate-ratio, $f/1.1$ (actual at focal surface), 380- to 600-nm-passband instrument with a uniform 5-lp/mm (50% MTF at edge) resolution over the whole of a 150-mm-diam scintillator, imaged onto an 18-mm detector surface.

angles, compared with the performance of the prototype shown in Fig. 3.

When scaling to EPDs >250 mm with relative apertures greater than $f/1.5$, it has been found best to apochromatize the design in the same way, but also to achromatize the field lens, as mentioned previously, to limit the lateral chromatic aberration that becomes evident at such high levels of correction. Despite the improved aberration control so afforded, it has been found necessary to exclude wavelengths shorter than 480 nm in the simple designs initially explored.

The second design study, with these additional components, and with an EPD of 260 mm, $F=366$ mm, $f/1.4$, 480- to 1500-nm passband, and a Newtonian configuration, is listed in Table 4, and the layout shown in Fig. 7. The use of the Newtonian configuration reduces the spherical aberration of the intermediate image, compared to that of a

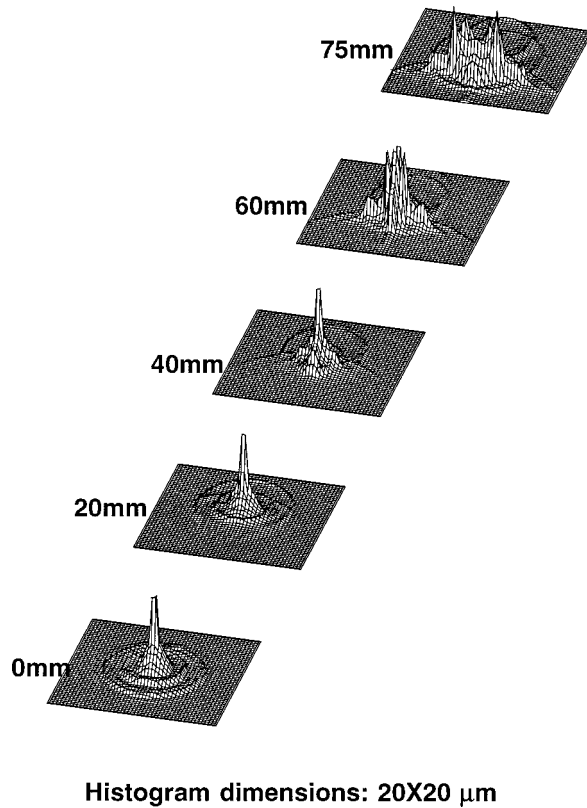


Fig. 5 Performance of the BN-2 KiwiStar supplied to a physics group at LANL. The off-axis dimensions are those at the scintillator, and the computed PSF histograms show the distribution of illumination at the fiber faceplate image surface. The passband is 380 to 600 nm.

Table 2 Optical prescription of the BN-2 scintillography KiwiStar. The 150-mm-diam scintillator is located 3400 mm in front of a 1-in.-thick BK 7 porthole, and the K 5 window is the secondary support and dust seal. The chromatic corrector doublet is air-spaced 0.1 mm. The final 120-deg. fold is not included. The performance is illustrated in Fig. 5. Aspheric coefficients of surface 14: $A_2 = -1.63E-05$, $A_4 = +7.75E-09$, $A_6 = -7.28E-13$, $A_8 = -2.9E-17$, $A_{10} = -4.3E-21$.

Surface	Glass	Spacing (mm)	Curvature (mm^{-1})	Radius (mm)	Mirror or lens	Inner diam (mm)	Outer diam (mm)
1			0		L		420
2 Porthole	BK 7	25.400	0		L		420
3		79.600	0		L		393
4 Window	K 5	10.000	0		L		393
5 Sph. prim.		785.000	-0.000625000	-1600.00	M	150	500
6 Sph. sec.		-740.000	-0.001162791	-860.00	M		156
7		537.000	0.003262640	306.50	L		85
8 Field	BK 7	30.000	-0.001287000	-777.00	L		85
9		468.207	0.008474576	118.00	L		125
10 Meniscus	SK 16	18.000	0.010002800	100.00	L		125
11		87.693	0	Flat	L		130
12 Doublet	SK 16	10.000	0.000931966	1073.00	L		130
13 Air space		0.100	0.000931966	1073.00	L		130
14 Ap. stop	F 2	10.000	Aspheric 0	flat	L		130
15 Relay		400.000	-0.002500640	-400.00	M		333
16 Fiber plug		-262.548	-0.003700000	-270.27	L		18

Table 3 Optical prescription for an apochromatic version of the KiwiStar prototype. The only material change is the replacement of the doublet chromatic corrector with a triplet. As with the prototype, all surface radii are from the present tool stock⁶ in the optical workshop of Industrial Research Limited. The performance is illustrated in Fig. 6. Aspheric coefficients of surface 12: $A_2 = -3.99\text{E}-05$, $A_4 = +1.21\text{E}-07$, $A_6 = -7.28\text{E}-11$, $A_8 = -2.72\text{E}-14$.

Surface	Glass	Spacing (mm)	Curvature (mm^{-1})	Radius (mm)	Mirror or lens	Inner diam (mm)	Outer diam (mm)
1 Sph. prim.			-0.00098668	-1013.52	M	97	265
2 Sph. sec.		-356.90	-0.00152300	-656.60	M		100
3		262.00	0.00722750	138.36	L		58
4 Field	SK 11	18.00	-0.00257140	-388.90	L		58
5		167.411	0.01618909	61.77	L		55
6 Meniscus	SK 4	19.82	0.02384359	41.94	L		55
7		11.369	0	Flat	L		50
8 Filter	BK 7	3.00	0	Flat	L		50
9		20.98	0	Flat	L		52
10 Triplet	KzF N2	3.50	-0.00469040	-213.20			52
11	FK 51	3.00	0.00469040	213.20	L		52
12 Ap. stop	KzF N2	3.50	Aspheric 0	Flat	L		52
13 Fold		65.00	0	Flat	M	38	100
14 Relay		-82.20	0.00678196	147.45	M	58	140
15		98.067	0.03018048	33.13	L		12
16 Petzval	SF 2	1.00	0	Flat	L		12

Cassegrain configuration of the same NA, permitting the highest level of aberration control in the complete system. A blur spot diameter of $\sim 2 \mu\text{m}$ is achieved over most of a 20-mm-diam (3.1-deg) flattened field, providing $\sim 10^8$ resolvable points at $f/1.4$. The performance is shown in the PSF histograms of Fig. 8. Diffraction effects are not included.

Clearly, this design could be scaled up to the limit where the aberration blur is still just acceptable for any given detector. For example, scaling up $4\times$ could result in a 1-m, $f/1.5$ system with an 80-mm-diam flat focal plane covering 3.1 deg with better than 2-arcsec resolution over a 1000-nm-wide passband. Such a system may be of some use in scientific and astronomical applications. At this scale, the only significant difficulty would be in the availability of the ~ 300 -mm-diam blanks for the chromatic corrector's special glasses.

KiwiStar design data are remarkably noncritical, as demonstrated in this variant by the use of a symmetrical triplet chromatic corrector. Unconstrained optimization procedures suggest a triplet with an asymmetry that varies according to the input specification of image-resolution uniformity, but the symmetrical version is negligibly different in overall aberration correction, while offering significant fabrication advantages.

The equal-radii doublet field lens of Table 4 was chosen on a similar basis. Perhaps the most comprehensive demonstration of adaptability is that every glass and every surface radius in the prototype KiwiStar and in the computed apochromatized version (see Tables 1 and 3) was chosen from the existing glass stock and tool range⁶ in the optical workshop of Industrial Research Limited. Some of the radii departed significantly from the unconstrained optimized

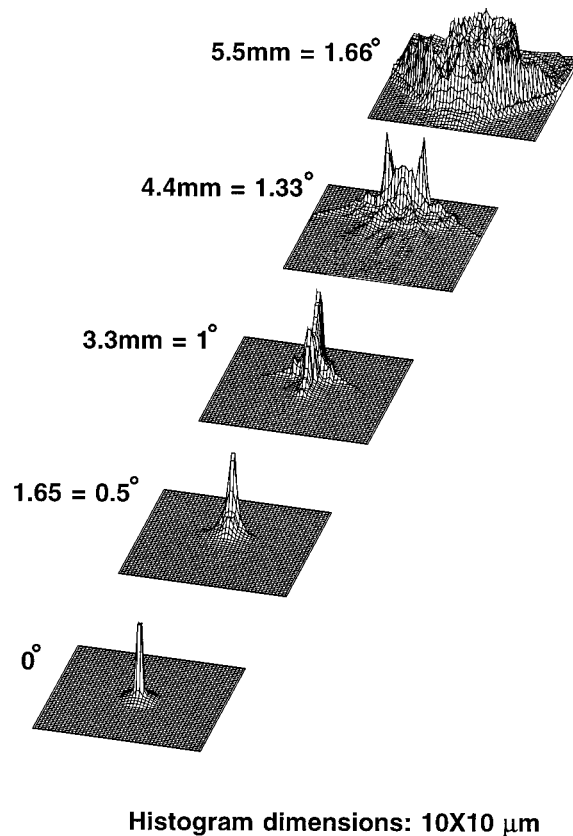


Fig. 6 Performance of the apochromatic improved prototype KiwiStar. The speed is $f/1$ (geometric), $t/1.2$ (photometric), passband 480 to 1014 nm. Note that these PSF histograms cover only 1/4 the area of those in Fig. 3.

Table 4 Optical prescription of a 260-mm-diam, f/1.4 apochromatic variant of the KiwiStar system. The second mirror is listed as folding the system through 180 deg, but in practice would act as a Newtonian diagonal, so as to place the entire fast focal reducer outside the incident beam. If this diagonal were to be relocated within the focal reducer, close to the F2/SK 16 field lens, as shown in Fig. 7, the central obscuration would be only 12% of the pupil area. This design is scalable up to pupil diameters ~1 m. The performance is illustrated in Fig. 8. Aspheric coefficients of surface 11: $A_2 = -7.20E-06$, $A_4 = +1.43E-08$, $A_6 = -6.08E-12$, $A_8 = -1.03E-15$.

Surface	Glass	Spacing (mm)	Curvature (mm ⁻¹)	Radius (mm)	Mirror or lens	Outer diam (mm)
1 Sph. prim.			-0.00040000	-2500	M	380
2		-1240.000	0.00440723	226.9	L	75
3 Doublet	F2	-10.000	-0.00440723	-226.9	L	75
4 Field	SK 16	-10.000	0	Flat	L	75
5 Fold		-30.900	0	Flat	M	160
6		200.000	0.01250000	80	L	70
7 Meniscus	BK 7	13.000	0.01492537	67.02	L	70
8		57.100	0	Flat	L	70
9 Symm.	KzF N2	5.000	-0.00141243	-708	L	70
10 Triplet	FK 51	5.000	0.00141243	708	L	70
11 Ap. stop	KzF N2	5.000	Aspheric 0	Flat	L	68
12 Relay		300.000	-0.00333333	-300	M	210
13		-204.360	-0.01698370	-58.88	L	21
14 Petzval	SK 16	-1.500	0	Flat	L	21

values, resulting in a redistribution of illuminance across each PSF, but the resolution performance of the system was virtually unaffected. Similarly, the prescriptions of the BN-2 KiwiStar and of the Newtonian format design were adapted to the same tool range, for cost reduction in the former and as a check on economic realization for the latter.

5 Other Applications

Any optic with a combination of high values of NA, field angle, resolution, and spectral bandwidth obviously has a role to play in low-light-level scenarios—astronomy and surveillance are obvious examples. Scintillography, as rep-

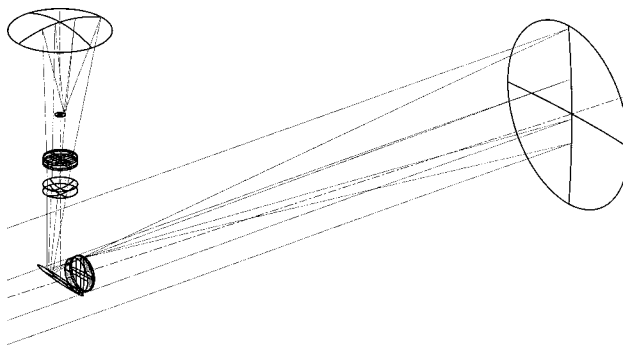


Fig. 7 Layout of the f/1.4 apochromatic KiwiStar design of Newtonian format, listed in Table 4. In this layout, the Newtonian fold has been included in the focal reducer, resulting in only 12% pupil area obscuration. The spherical primary mirror has a working aperture of f/4.8 and must be 45% oversize for zero vignetting in a 3.125-deg field diameter.

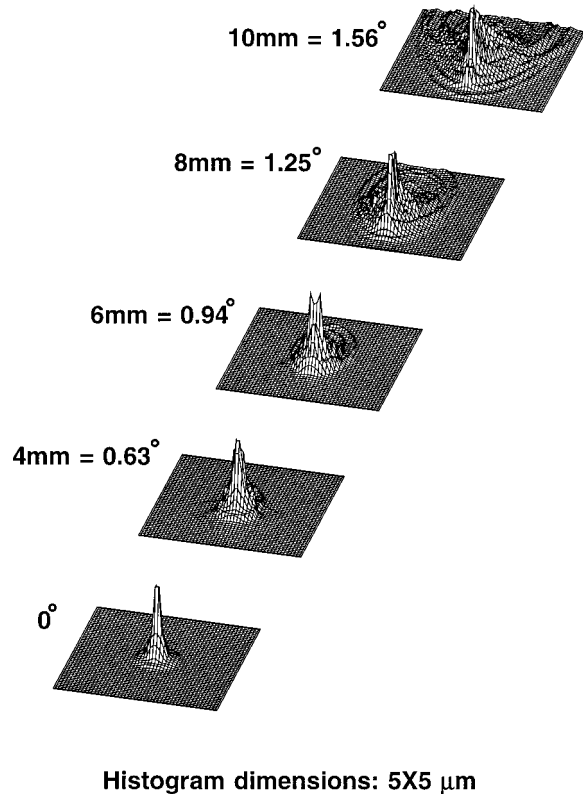


Fig. 8 Performance of the KiwiStar variant illustrated in Fig. 7. Note that the computed ray-intercept PSF histograms would be strongly modified by diffraction effects at the micrometer scale shown.

resented by the LANL requirement, exemplifies the scientific demands. A further aspect, however, is the opportunity, presented by a high image illuminance, to employ very high shutter speeds in well-illuminated fast-transient event recording, such as explosives trials—or, in a less exotic scenario, sports events—where an image series with high time resolution may have to be acquired at long range.

Moreover, the KiwiStar system can be applied to thermal infrared imaging in all the above scenarios. One design has been computed, otherwise identical to the prototype, but in which germanium and synthetic sapphire refractive components replace the optical glass of the visible-NIR KiwiStar. This design is apochromatic from 3.7 to 5.5 μm and, indeed, diffraction-limited over most of the field. In general, a KiwiStar design can be created in any spectral band for which there is an appropriate set of refractive and reflective materials.

6 Conclusions

By optically coupling the concentricities of a primary spherical catoptric and a focal reducer spherical catadioptric, it is possible to achieve a large improvement over conventional designs in ease of fabrication and in combined image illuminance, resolution, and spectral bandwidth. For example, medium- to large-size (200-mm to 1.2-m EPD) Schmidt cameras require full-diameter achromatic aspherical corrector plates, and are generally limited to speeds $\sim f/2$ and $\sim 300\text{-nm}$ spectral bandwidths, in order to achieve a 100% encircled energy radius of 5 μm . For KiwiStar designs, at speeds $\sim f/1$, the resolution and spectral bandwidth constraints are generally those of the detector device. Additionally, refractive components are significantly subdiameter, and the only full-aperture-diameter component is the spherical primary mirror, providing useful fabrication and cost advantages.

The resulting optic is ideally suited to electronic imaging devices and can be designed for any passband in the spectrum for which there exist suitable refractive and reflective media.

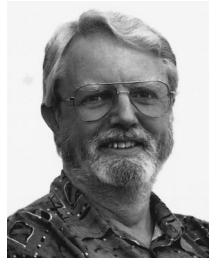
The two instruments constructed to date have shown that fabrication requires no unusual workshop techniques and that mechanical tolerances are not critical.

Acknowledgments

Invaluable advice and support in the later phases of design development was provided by Mr. Norman Rumsey, Mr. Garry Nankivell, and the staff of the optical and mechanical workshops of Industrial Research Limited (IRL), especially Dave Cochrane (optical fabrication) and Tim Wyatt (mechanical design and fabrication). The earliest phase of development was made possible by the managerial support of Mr. Peter Connor; the later phase, by Business Development, IRL.

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David Beach is a physicist specializing in (mainly optical) measurement instrumentation. Fourteen years at AWRE Aldermaston and UKAEA Culham was spent devising seismographs, thermography systems, CO₂ laser surgery devices, and thermonuclear-fusion diagnostic spectrographs. Emigrating to New Zealand in 1973 led to ultrasound, x-ray, and machine-vision investigations in the Department of Scientific and Industrial Research and later its commercial metamorphosis, Industrial Research Limited, but the 1986 apparition of Halley's comet stimulated the devising of the KiwiStar design principle described in this paper. He is a Member of the New Zealand Institute of Physics and a Member of the Royal Society of New Zealand.