THE MERSENNE - SCHMIDT TELESCOPE

R. V. Willstrop

Institute of Astronomy, The Observatories, Madingley Road, Cambridge CB3 OHA, U.K.

Summary. A three-mirror telescope is described which covers a field 4° in diameter at f/1.6 with images smaller than 0.31 arcsec total spread (0.17 arcsec r.m.s.); an alternative version, also f/1.6, covers a field 2° in diameter with images smaller than 0.049 arcsec (0.023 arcsec r.m.s.). Both forms of this telescope are fully baffled against sky fog contamination, the illumination is uniform over the central 2° field and decreases by about 13 per cent at the edge of the 4° field, and the tube length is little more than the focal length.

The insertion of a plane parallel filter in such steeply converging light introduces spherical aberration and coma, but these aberrations can be corrected adequately by adjustments to the mirror spacings.

1. Introduction. The problems of building a large ($\gtrsim 5$ m) ground-based telescope at a reasonable cost, and using it efficiently despite a seeing tremor disc that is very rarely smaller than 0.5 arc seconds in diameter even at the best sites, are well known. It is the solutions that are elusive.

Because a significant fraction, sometimes approaching half, of the total cost of a large telescope of conventional design is accounted for by the dome and building, substantial savings can be made if the telescope can be fitted into a smaller dome. The tube length above the balance point is the most important factor determining the dome size.

A large telescope might be judged to be 'efficient' if it could be used both for imaging (during dark time) over fields which, if not quite as large as those covered by a Schmidt camera, were say 4° in diameter, and also (during grey and bright moonlit time) for multi-object spectrography, using optical fibres to transfer the light of each of up to $\sim 10^2$ objects from the focus of the telescope to the entrance apertures of a small number of different spectrographs, giving low resolving power for the fainter objects and higher resolving power for the brighter, all in comparable but not necessarily identical exposure times. A field of 4° is needed to include a useful number of cosmologically significant objects, such as radio-quiet QSOs of V = 20 or brighter that can be identified by transmission grating slitless spectroscopy on a 4 m reflector (Hoag & Smith 1977) or U.K. Schmidt objective prism plates (Clowes & Savage 1983), and for which spectra with better resolution are required.

With the exception of the Irenee DuPont Telescope (Bowen & Vaughan 1973) which covers a field $2^{\circ}.1$ in diameter, most large telescopes now in operation or planned have

Proceedings of the IAU Colloquium No. 79: "Very Large Telescopes, their Instrumentation and Programs", Garching, April 9–12, 1984.

fields limited to 1° in diameter or smaller, and those which use lenses or an aspheric plate as a field corrector are inevitably restricted to a moderate range of wavelengths (e.g. the AAT triplet corrector was designed for the range 380 - 600 nm, the doublet for 365 - 852 nm (Wynne 1974)).

Experiments are in progress at Siding Spring on the use of optical fibres at the focus of the U.K. Schmidt telescope to transfer images to a stationary spectrograph or other instrument. The tube length of a Schmidt would make a large dual purpose (light bucket/field imaging) telescope of this form very costly, and the glass required for an achromatic corrector might not be available in sufficiently large pieces of suitable homogeneity.

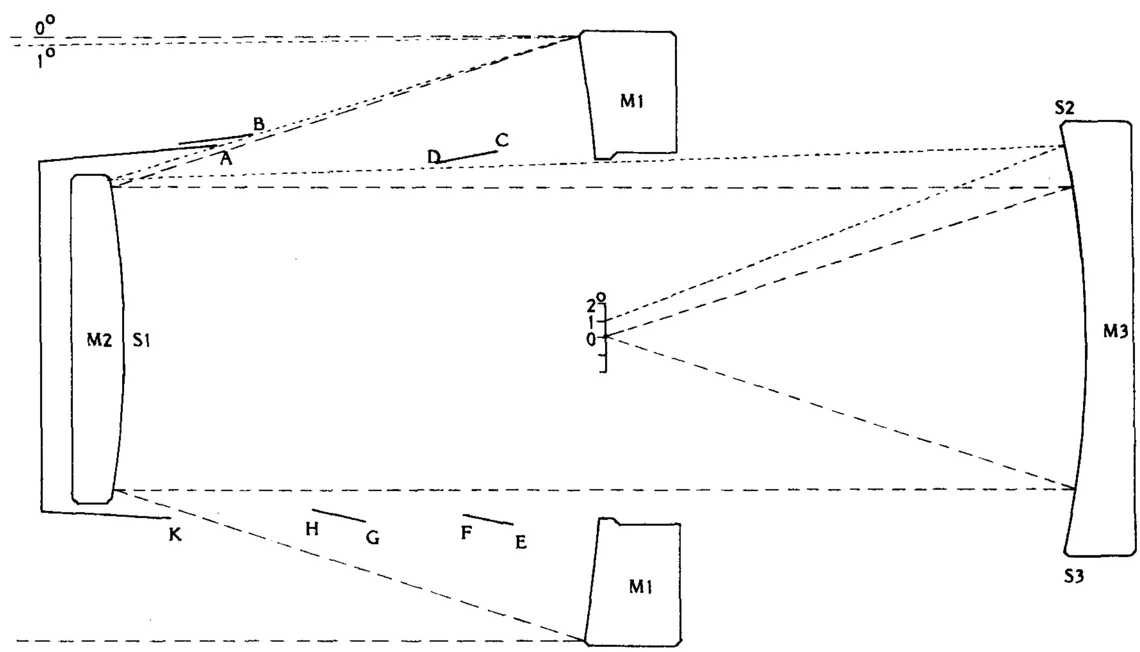

Figure 1. Arrangement of the Mersenne-Schmidt telescope. M1 is approximately paraboloidal, and M2 and M3 are both approximately spherical. The details of the design are given in Table 1. Sky fog baffle A is sufficient to shield the central 2° diameter of the field from light that has been reflected only in the tertiary mirror. To shield the full 4° field this baffle can be extended to B, or A can be used with the conical baffle CD. The obscuration can be reduced by the arrangement shown in the lower half of the figure. The dimensions of the baffles are given in Table 2. The positions of sources and sensors for optical alignment are S1, S2 and S3; see Section 7 of the text.

https://doi.org/10.1017/S025292110010853X Published online by Cambridge University Press

2. The Mersenne-Schmidt. The three-mirror telescope described here, provisionally named the Mersenne-Schmidt (Willstrop 1984, hereinafter Paper I), meets the criteria of a short tube length (see Figure 1 and Table 1, both adapted from Paper I), perfect achromatism, and seeing-limited images over a field 4° in diameter (Figure 2), or nearly diffraction-limited images at 5m aperture over a field of 2° (Figure 3).

This system is based in part on one described by Paul (1935) and independently discovered and improved by Baker (1969), but differs from it in two important respects:

Table 1. Construction details of f/1.6 Mersenne-Schmidt.

Focal length 8000 mm. Dimensions in mm.

Component	Radius	Distance	Material	Diameter
Mirror 1	-16000.0			5000.0 (2969.0)
		4000.0	air	
Mirror 2	8000.0			2643.0
		8000.0	air	
Mirror 3	-8000.0			3530.0
		4000.0	air	
Focal surface	8000.0			558.5

Notes:

The second diameter for the primary mirror refers to the perforation.

The mirrors of version 1 (images under 0.049 arcsec over 2 degree field) have profiles given by the power series:

$$x_1 = -3.125 \times 10^{-5} r^2 \quad -5.8428 \times 10^{-23} r^6 \quad -6.355 \times 10^{-31} r^8$$
$$x_2 = 6.25 \times 10^{-5} r^2 \quad +2.44237 \times 10^{-13} r^4 \quad +1.34267 \times 10^{-20} r^6 \quad +6.136 \times 10^{-28} r^8$$
$$x_3 = -6.25 \times 10^{-5} r^2 \quad -2.44141 \times 10^{-13} r^4 \quad -2.20914 \times 10^{-21} r^6 \quad -2.921 \times 10^{-29} r^8$$

For comparison with mirrors 2 and 3, the nearest sphere fits the series:

$$x_s = 6.25 \times 10^{-5} r^2 \quad +2.441406 \times 10^{-13} r^4 \quad +1.907373 \times 10^{-21} r^6 \quad +1.86 \times 10^{-29} r^8 \quad +2.1675 \times 10^{-37} r^{10}$$

The surface of least r.m.s. image spread is: $x_f = -6.2571814 \times 10^{-5} r^2$

The mirrors of version 2 (images under 0.31 arcsec over 4 degree field) have profiles given by the power series:

$$x_1 = -3.125 \times 10^{-5} r^2 \quad -4.04734 \times 10^{-23} r^6 \quad -1.574 \times 10^{-30} r^8$$
$$x_2 = 6.25 \times 10^{-5} r^2 \quad +2.442386 \times 10^{-13} r^4 \quad +1.2168 \times 10^{-20} r^6 \quad +8.506 \times 10^{-28} r^8$$
$$x_3 = -6.25 \times 10^{-5} r^2 \quad -2.441405 \times 10^{-13} r^4 \quad -2.10116 \times 10^{-21} r^6 \quad -3.657 \times 10^{-29} r^8$$

https://doi.org/10.1017/S025292110010853X Published online by Cambridge University Press

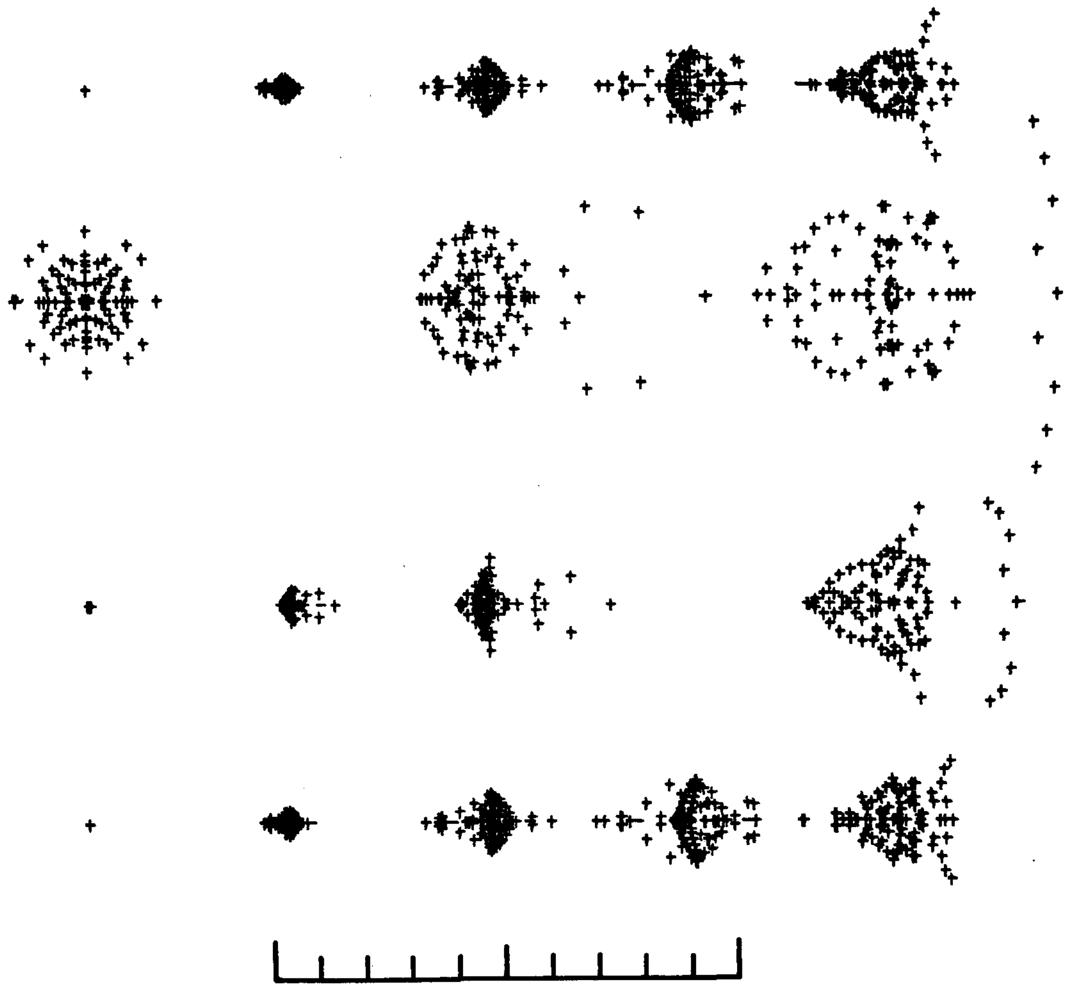

Figure 2. Optical performance of the Mersenne - Schmidt telescope with 4° field. Each row shows images on axis (left), $1^{\circ}.0$ and $2^{\circ}.0$ off axis; some rows also show images $0^{\circ}.5$ and $1^{\circ}.5$ off axis. Top row: Design as in Table 1. Second row: A filter 3 mm thick has been inserted in the converging light. The mirror spacings are unchanged at 4000.0 and 8000.0 mm, but the detector has been refocussed for minimum r.m.s. image spread. Spherical aberration and coma have appeared. The images at $0^{\circ}.5$ and $1^{\circ}.5$ off axis are omitted to avoid confusion. Third row: Spherical aberration has been corrected on axis by reducing M_1M_2 to 3999.37 mm. Coma remains. The image at $1^{\circ}.5$ off axis has been omitted. Bottom row: Spherical aberration and coma are corrected with mirror spacings of 3999.40 and 8004.50 mm respectively. Note the similarity to the top row.

https://doi.org/10.1017/S025292110010853X Published online by Cambridge University Press

(a) Both Paul and Baker considered the second and third mirrors to be a zero-power corrector for the prime focus of an existing paraboloidal primary mirror, which could not be given a large perforation without affecting its performance at Cassegrain or coudé foci. It should be noted that Baker had earlier (Dimitroff & Baker 1945) described the system with a large perforation and the tertiary mirror behind the primary, but by 1969 he had discarded this form. The perforation of the primary, and placing the tertiary mirror as far behind it as the secondary is in front, makes it possible to reduce the angular magnification produced by the primary and secondary mirrors from x3 (in Paul's design) or more (in Baker's) to x2, while keeping the final focal ratio equal to that of the primary mirror. This allows the field to be increased substantially; in the present design the Schmidt-like combination of the secondary and tertiary mirrors is required to cover a field 8° in diameter in image space while the system as a whole covers 4° in object space.

(b) The second important difference is in the mirror asphericities. Paul noted that Seidel spherical aberration, coma and astigmatism were corrected with a primary paraboloid and two spherical mirrors. Baker (1969) chose to flatten the field by giving the secondary and tertiary mirrors different (numerical) radii of curvature, and making the secondary ellipsoidal. He also required an 'aconical' deformation of the

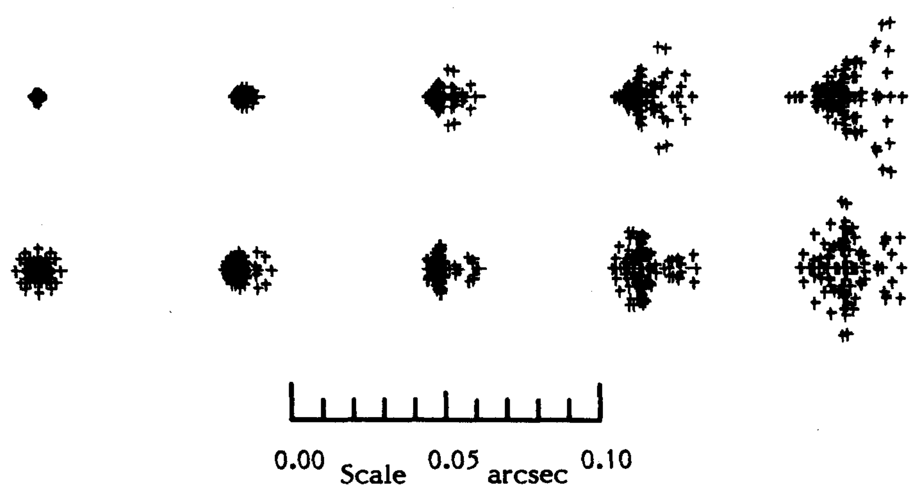

Figure 3. Optical performance of the Mersenne - Schmidt telescope with 2° field. Each row shows images on axis (left), $0^{\circ}.25$, $0^{\circ}.50$, $0^{\circ}.75$ and $1^{\circ}.00$ off axis. Top row: Design as in Table 1.

Bottom row: A filter 3 mm thick has been inserted in the converging light, and the resulting spherical aberration and coma have been corrected by changing the mirror spacings from 4000.0 and 8000.0 mm to 3999.42 and 8004.83 mm respectively. The detector has been refocussed for minimum r.m.s. spread within each image. The intermediate stages of correction (or lack of it) shown in Figure 2 are omitted as they could not be included on the larger scale used in this Figure.

https://doi.org/10.1017/S025292110010853X Published online by Cambridge University Press

secondary, which may be interpreted as a figuring proportional to r^6. Baker retained the paraboloidal primary and spherical tertiary mirrors. In the present design it has been shown that at f/1.6 the correction of higher order spherical aberration requires terms in both r^6 and r^8 in the profile of the secondary mirror, and to correct higher order types of coma and astigmatism simultaneously with the spherical aberration it is necessary to figure all three mirrors. The separations and profiles of the mirrors of two possible f/1.6 systems of 5m aperture, covering 2° or 4°, are given in Table 1.

The details of the method by which these specifications were reached were given in Paper I. Automatic computer optimisation has not been used to obtain the data in Table 1, but it is to be expected that some further improvement would be obtained by this means. R. G. Bingham (private communication) has shown that the ray-theoretic r.m.s. image spread at the edge of the field can be reduced by at least 30 per cent, but he noted that, as the images in the version covering 2° field were then nearly diffraction-limited it would be desirable to repeat the computation, minimising the optical path differences.

3. Sky fog baffles. Three different arrangements of sky fog baffles are shown in Figure 1. In the upper half of the Figure, the conical baffle A around the secondary mirror is sufficiently large to prevent any light from the sky passing through the perforation in the primary mirror if it is parallel to or within 2° of the axis of the system. Light that is slightly more inclined to the axis can enter and will illuminate a narrow crescent of the tertiary mirror, but will be focussed outside the field 2° in diameter because the image surface is placed at the paraxial focus of the tertiary mirror for parallel light, and the narrow illuminated crescent is in effect at the edge of a spherical mirror of aperture f/1.6. The central obstruction is 40.7 per cent by area, and this leads to a redistribution of light from the central maximum into the surrounding rings of the diffraction pattern. See Figure 4. In a space telescope designed with a field 2° in diameter the manufacturing errors would need to be kept within very close tolerances to allow the geometrical aberrations and diffraction effects to be detectable; in a ground-based telescope the seeing will probably always predominate.

To shield the larger field 4° in diameter, there are three options: baffle A can be extended to B, increasing the obscuration to 45.43 per cent, or A can be used with the ring baffle CD (42.13 per cent), or two ring baffles EF and GH can be used with a smaller baffle K around the secondary mirror (41 per cent obscuration). The baffles CD, or EF and GH, break up the light-collecting area and divert some light even further from the centre of the diffraction pattern, but the geometrical aberrations are larger in the 4° system, and these and the seeing are again expected to predominate.

The central obstruction could be slightly reduced, while continuing to cover a given field, by making the focal ratio even faster than f/1.6, but this would lead to greater manufacturing difficulties.

Details of the baffle positions and radii are given in Table 2.

Table 2. Sky fog baffles. Dimensions in mm.

Baffle	Function	Radius		Height
		Outside	Inside	
A	Shields central 2 degrees diameter	1595	1589	3235
B	Shields 4 degrees diameter	1685	1679	2935
C	With A, shields 4 degrees	1550	1537	900
D		1451	1438	1400
E	Together, baffles E - K shield	1536	1523	800
F	a field 4 degrees in diameter.	1459	1446	1200
G		1510	1497	2020
H		1407	1394	2470
K		1480	1474	3650

Notes. Data are rounded to the nearest mm. The thickness of the baffles is assumed to be 0.5 inch (13 mm) except the edges of baffles A, B and K which are 0.25 inch (6 mm). Radii are measured from the optical axis of the telescope, and heights above the pole of the primary mirror. For further explanation see the text, Section 3.

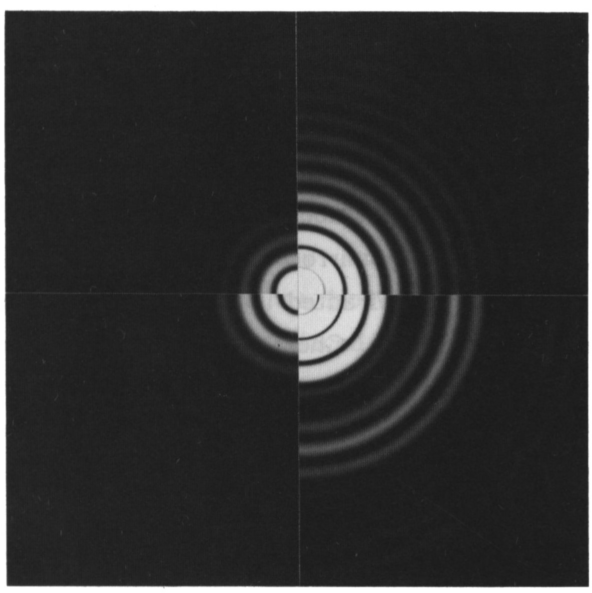

Figure 4. Diffraction from a circular aperture: top, an unobstructed circular aperture; bottom, a circular aperture of the same diameter as above, but with a central, circular, obstruction covering approximately 40 per cent of the area. Left, short exposure; right, long exposure (ratio of exposures 1:8).

https://doi.org/10.1017/S025292110010853X Published online by Cambridge University Press

4. Direct photography. The three-mirror systems specified in Table 1 are designed for use without a filter. If a filter is inserted it results in spherical aberration, coma and longitudinal chromatic aberration. The monochromatic images can be corrected by adjustments to the spacings of the mirrors as shown in Figure 2. The performance of the system designed to cover a field 4° in diameter is shown by spot diagrams of the ray-theoretic images, in the top row. The result of inserting a filter 3 mm thick is shown in the second row; some images are omitted to avoid confusion. The axial image can be corrected by a small reduction in the separation of the primary and secondary mirrors (row 3). Coma can also be corrected, by increasing the separation of the secondary and tertiary mirrors, and this requires a small further adjustment to be made to the separation of the primary and secondary mirrors to restore the correction of the spherical aberration on axis (bottom row).

The performance of the system designed to cover a field 2° in diameter is shown on a larger scale in Figure 3, without a filter in the top row, and with a filter 3 mm thick and with the mirror spacings adjusted in the bottom row. The intermediate stages of correction (or lack of it) could not be shown at this scale and are therefore omitted.

Compared with a Schmidt camera used for direct photography, fewer ghost images are to be expected. If no filter is required, there can be no ghosts. When a filter is used, close to the focus, there will be ghosts arising from internal reflections within the filter, and from reflections at the emulsion followed by either surface of the filter. The ghost images characteristic of a Schmidt camera, resulting from reflections in the aspheric corrector of light scattered or reflected from the emulsion, cannot occur.

5. 'Objective prism' photography. A thin compound zero-deviation prism may be inserted in the path of the parallel light above the plateholder to disperse the light of all objects in the field. The tertiary mirror would need to be adjusted to ensure that its apparent centre of curvature, as refracted in the prism, was restored to coincidence with the pole of the secondary mirror. Ghost images analogous to those caused by the corrector plate of a Schmidt camera will be formed by such a prism. The aperture of the prism need be little more than half of that of the telescope, but to obtain the same dispersion as a true objective prism would give on a telescope of the same focal length the angle would need to be doubled.

6. Multiobject spectrography. Because the focal surface of the Mersenne-Schmidt is within the beam of parallel light, there is little space to instal a spectrograph of any size there. While a very small fraction of the available field could doubtless be transferred to a more accessible position on the tube, or even to a stationary (coudé) focus, this would require several auxiliary mirrors and entail considerable losses of light.

The alternative is to use optical fibres to convey the light of selected objects at random positions within the 4° field to one or more spectrographs at a convenient position, perhaps on the floor of the dome. Observations have already been made by means of optical fibres by Hill et. al. (1980) and Ellis et. al. (1984), using smaller fields and less steeply converging light. Efficient quartz fibres are unable to convey cones of light as fast as f/1.6 and it would therefore be necessary to use a small lens to enlarge the scale of the image of each object, and reduce the convergence of the light entering the fibres.

If the convergence of the light were to be changed from f/1.6 to f/8 the image scale would be changed from about 40 μm/arcsec (for an aperture of 5 m) to about 200 μm/arcsec. At this scale the seeing blur would fill a number of fibres arranged in hexagonal close packing; at the entrance aperture of the spectrograph the other ends of the fibres could be arranged in a line, so that the fibres acted as an image slicer. In this way one of the more serious problems of using a large telescope efficiently, i.e. the problem of matching the images to a spectrograph without degrading the seeing and without wasting much of the light at the slit, would be partially solved. Fibres used as an image slicer cannot be as efficient as some other devices, because some of the light will fall between into the space between three fibres, and some into the cladding of each fibre, but this loss is compensated by the possibility of recording the spectra of many objects simultaneously.

7. Optical alignment. A telescope of this type will need to be aligned accurately if it is to perform well. The axes of all three mirrors should be coincident, and the spacings of the mirrors must also be correct.

The centre of curvature of the tertiary mirror should coincide with the pole of the secondary mirror, and there is space near the centre of the secondary to place there a light source and sensor which could detect misalignment of the third mirror. An area around the centre of the secondary mirror could be ground and polished spherical with a radius equal to the distance from the secondary to the tertiary mirror, and a second light source and sensor, placed at opposite ends of a diameter of the tertiary mirror, could be used to check the squaring-on of the secondary. Either the source or the sensor would need some correction to allow for the astigmatism that would occur in an oblique reflection in the secondary mirror.

Alignment of the primary is more critical, and more difficult to test. There is a narrow annulus of the primary mirror around the central perforation, which is not illuminated by starlight and which might be ground and polished spherical with its centre of curvature coinciding with the centre of the secondary mirror. This might be used to check the position of the primary mirror.

The most certain check on the correct adjustment of the telescope will be its performance. Loibl (1980) has demonstrated a form of the Hartmann test, using photographic recording, which uses a small collimating lens and a miniature Hartmann screen at its focus, with the detector spaced a few cm behind the screen. If the photographic plate was replaced by a CCD this would permit the image quality, for an off-axis star, to be monitored continuously. Equipment of this type is under construction at Cambridge and will be used in optical tests of the telescopes at the Roque de Los Muchachos Observatory, La Palma. Computer simulations have shown that simple aberrations such as Seidel spherical aberration, coma and astigmatism can be recognised and their amount estimated accurately; it is only necessary to provide servo systems to move the mirrors and programs to compute the movement required.

8. Conclusions. There appear to be no insuperable difficulties in the construction and use of this three-mirror telescope.

References.

Baker, J.G., 1969. Proc. I.E.E.E. AES-5, 261.

Bowen, I.S. & Vaughan, A.H., 1973. Applied Optics 12, 1430.

Clowes, R.G. & Savage, A., 1983. Mon. Not. R. astr. Soc., 204, 365.

Dimitroff, G.Z. & Baker, J.G., 1945. Telescopes and Accessories, (p 105). Blakiston, Philadelphia. (The Harvard Books on Astronomy).

Ellis, R.S., Gray, P.M., Carter, D. & Godwin, J., 1984. Mon. Not. R. astr. Soc., 206, 285.

Hill, J.M., Angel, J.R.P., Scott, J.S., Lindley, D. & Hintzen, P., 1980. Astrophys. J., 242, L69.

Hoag, A.A. & Smith, M.G., 1977. Astrophys. J., 217, 362.

Loibl, B., 1980. Astron. Astrophys., 91, 265.

Paul, M., 1935. Rev. Opt. theor. instrum., 14, 169.

Willstrop, R.V., 1984. Mon. Not. R. astr. Soc., In the press.

Wynne, C.G., 1974. Mon. Not. R. astr. Soc., 167, 189.