General optical description of the 4.2-metre Herschel Telescope

RGO/La Palma Technical Note No. 9

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September 1984

Introduction

The 4.2-metre Herschel telescope is an alt-azimuth Instrument. Conventional Cassegrain optics are used. The focal stations to be Implemented are the prime focus, Cassegrain focus, two Nasmyth stations and a “broken Cassegrain” position on the tube. Only one Cassegrain secondary mirror is required. Alternative secondary mirrors were discussed but are not being implemented. Holes in the structure may allow for the eventual addition of a coud , light path emerging from the building for an interferometric link.

The optical characteristics of the mirrors of the 4.2-metre telescope are summarised in Table I. The primary mirror will have a clear aperture of 4200 mm diameter and a nominal focal length of 10,500 mm resulting in a focal ratio of 2.5 for the mirror alone. The mirror is specified in terms of interferometric tests and is expected to provide performance at least equivalent to that of the Anglo-Australian Telescope. The main optical diagram is on drawing number M125-T, reproduced here as Appendix D.

Prime Focus

The focus of the uncorrected paraboloid primary would show strong coma off-axis, the length of the coma figure being three per cent of the distance of the star from the centre of the field. To overcome this a three-lens corrector (Fig. 1) will be used to give improved off-axis images. The theoretical aberrations are shown by the spot diagrams in Fig. 2. A curve showing the nominal vignetting occurring at field diameters larger than about 40 arc minutes is given in Fig.3. (For very accurate photometry, this should be checked experimentally as it will depend on the quality of the lens coatings and other factors.) Other parameters of the corrected prime focus and other foci are given in Table II. A note on the use of colour filters is given in Appendix A. Dimensions of the prime focus corrector are given in Appendix B.

Table I

Summary of nominal mirror characteristics for the 4.2-metre Herschel Telescope

Element	Shape	Aspher-icity	Working (Total) Diameter (mm)	Equiv. focal length (mm)	Separation from previous mirror (mm)	Material	Expn. Coeff. $(^oK)^{-1}$	Axial thickness (mm)
Primary	concave paraboloid	-1	4200 (4220)	10,500	(sag 105mm)	Cervit	$0.1\pm0.1 \times10^{-6}$	452
f/11 Secondary	convex hyperboloid	-2.5225	1001 (1020)	-3,115	8093	Zerodur	-0.7×10^{-6}	168
Nasmyth flat	flat	0	616x432 (635x441)		See diagram (Appendix D)	Cervit	$0.1\pm0.l \times10^{-6}$	51

Drawings

TC1 031 Secondary mirror
TC1 034 03 Nasmyth flat
TC1 030 03 Primary mirror
N-125-T Optical diagram

Note: this table and this document in general describe the design figures for the 4.2 metre telescope. The “as made” dimensions will be available later

Secondary Foci

There is one secondary mirror (f/11) which may be used to feed the Cassegrain, two Nasmyth and one “broken” Cassegrain focal stations. Any one of these f our stations is selected by the motion of the single Nasmyth flat mirror. The secondary mirror and flat are specified not to degrade the on-axis performance available from the primary mirror. Vignetting curves are shown in Fig. 3. Full details of the performance of the telescope, derived from observations, will be available after commissioning.

The theoretical aberrations off-axis at the Cassegrain and other secondary foci are indicated by spot diagrams in figures 4a, 4b and 4c. It may be noticed that these diagrams cover fields which are larger than the nominal 15 arc minutes diameter - the extended part of the field may be used by the autoguiders. Figure 4a shows the aberrations on a flat focal surface passing through the nominal focus on axis. Improved images at the edge of the f ield (Fig. 4b) may be obtained on a concave detector surface with radius of curvature 2200 mm. (This also illustrates the images which will be available at the edge of the field for a suitably focussed autoguider). Fig 4c shows images over a flat surface which is focussed for a compromise over the field. On the curved surface, the image spreads near the centre of the field are due to a coma figure whose length is equal to 0.16 per cent of the distance of a star from the axis.

Table II

Nominal optical characteristics of the 4.2-metre Herschell telescope

Focus	Focal length (mm)	Focal ratio	Exit pupil to focus (mm)	Field diameter (arc minutes) **(1)**	Diameter of central shadow (mm)	Scale arcsec /mm	Scale mm/ arcmin	Scale mm/ arcsec	Location of focus (mm from primary vertex) **(2)**	Focus/ Mirror shift **(3)**
Prime (without corrector)	10,500	2.5	10,500	See text	1220	19.64	3.05	0.051	10,500	-
Prime (with corrector)	11,700	2.8	-2,100 (beyond focus)	40 (60)	1220	17.63	3.40	0.057	10,570	-
Cassegrain and Nasmyth	46,200	11	12,850	Cass. 15 (19) Nasmyth 5 See Fig.3	1220	4.46	13.44	0.224	2,500	20
Nasmyth plus image rotator	47,053	11.20	12,000 to 17,000	2.5 (5)	1220	4.38	13.69	0.228	See diagram	21

Notes

(1) Unvignetted field; figures in brackets give partially vignetted field. See text for further details
(2) Prime focus in front, Cassegrain behind
(3) Movement of focus for unit movement of secondary mirror.

If the Cassegrain (and Nasmyth) focal points are shifted by moving the secondary mirror, the best theoretical image (without otherwise modifying the optics) enlarges to 0.18 arc seconds for each 100 mm of focus movement. This is shown in spot diagrams 4d, 4e and 4f.

A change of focal length occurs when the secondary mirror is moved and this effect is given In Table IIIA.

Image rotator

An image rotator will be available at one or both of the Nasmyth focal stations and is shown In Figure 5. Prisms of fused silica (Heraeus Homosil) with total internal reflection are used rather than mirrors to reduce both light loss and polarization. Lens surfaces on these prisms also extend the optical path as is necessary and maintain good image quality. The final element is a lens of UBK7 glass which is 1.5 mm thick on axis and is cemented to one of the fused silica prisms.

The back clearance is 303 mm. Some optical details of the image rotator are given In Table IIIB. Dimensions of the image rotator are contained in Appendix C. Outside the nominal, unvignetted region of 2.5 arc minutes there is a partially vignetted region with 50% vignetting at 5 arc minutes diameter. (Fig. 3).

Aberrations obtained with the image rotator are shown In Figs. 6a, 6b and 6c. Figure 6a illustrates the theoretical aberrations in the design. The images at 300 nm wavelength (not plotted) are 0.06 arc seconds larger in diameter than those shown for 330 nm wavelength. Figure 6b shows the degradation introduced if the secondary mirror is moved downwards by 7.38 mm, moving the final focus through the rotator outward by 155 mm. Figure 6c shows the effect obtained if the entire image rotator is moved outwards with the final image, maintaining the back clearance at about 300 mm. (See also Table IIIB).

The final image rotates at twice the angular speed of the rotator optics, which also change the image parity. When the rotator is inserted the telescope requires to be refocussed by moving the secondary mirror downwards by 3.82 mm. The position of the final focus when this is done is identical to that of the normal Nasmyth. The focal length and directions of principal rays (i.e. the exit pupil position) are also close to those of the normal Nasmyth focus (see Table II).

Table III (a)

Cassegrain and Nasmyth Foci

Outward movement of Cassegrain focus (mm)	Downward Movement of secondary mirror (mm)	Focal length (mm)	Spot diagram
0	0	46200	4a, 4b, 4c
50	2.46	46362	4d
100	4.92	46524	4e
150	7.38	46687	4f

Table III(b)

Nasmyth focus with image rotator

Outward movement of image (mm)	Movement of image rotator optics (mm)	Back clearance (mm)	Focal length (mm)	Spot diagram
0	0	303	47053	6a (designed)
155	0	458	47390	6b
151	154	300	47552	6c

The first line of the above table shows the characteristics of the instrument as designed. Other lines show typical results of moving the focus outwards by moving the secondary mirror (see text)

Appendix A

Colour filters at the prime focus of the 4.2-metre telescope

A plane-parallel glass slab such as a colour filter introduces a small amount of spherical aberration at the corrected prime focus. This aberration is equivalent to 0.5 μm of image diameter on an otherwise perfect image, per millimetre change of filter thickness at f/2.8, for a crown glass filter.

Another effect introduced by a plane-parallel colour filter or window is longitudinal chromatic aberration, i.e. wavelength dependent difference of focus. The shift of focus for a change δn in a refractive index n of a filter glass is given by $(\delta n/n^2)t$ where t is the thickness of the filter. Refocussing for a particular wavelength removes the effect for that wavelength. A wide wavelength range can be focussed to a mean position. This leads to a typical image diameter (on an otherwise perfect image) of 2 μm, per millimetre change of filter thickness, at each end of the wavelength range 365 to 852 nm. This applies for a crown glass filter when the focus is correct for the mean refractive index over this range.

The main general type of observation which uses a very wide wavelength range is spectroscopy. (Multiple-object spectroscopy is a possibility for the 4.2-metre prime focus). In such a case chromatic aberration is undesirable. Therefore, the corrector design is optimised with only a thin (three millimetre) colour filter so that the performance is essentially uniform for zero to six millimetres filter and window thickness. If a series of colour filters is to be used in any application they can be manufactured to a uniform optical thickness by cementing a plate of a clear glass to each filter. This will reduce focus adjustments as the filters are changed. Colour filters should be given an antireflection coating. When the filter consists of separate layers, the eventual outer surfaces should be coated before the layers are cemented.

Appendix B Prime Focus Corrector for 4.2-Metre Paraboloid

Giving 40 arc minutes field (one degree field partially vignetted)

Dimensions in mm

Radius of curvature (mm) (positive concave to image)	Separation (mm)	Material	Clear diameter (mm)	Full diameter (mm)
21000.0 (Vertex of mirror)	9530.00	air	4200	
417.06	40.25	UBK7	464	496
482.78	345.33	air	448	
856.44	15.00	UBK7	298	322
289.29	413.86	air	282	
489.77	30.52	Fused Silica	244	264
-1969.54	195.30	air		
infinity		focal plane		

Notes to Appendix B

1. Nominal radius of curvature of mirror applies to vertex of paraboloid.

2. Field diameters and distortion ratios. (These apply to the nominal primary mirror and lens. Final values will differ slightly).

Field diameter arc minutes	millimetres	distortion ratio (pincushion)
21.6	73.7	1.0019
30.0	102.5	1.0038
42.0	144.0	1.0075
60.0	207.4	1.0157

3. Equivalent focal length 11700 mm with nominal primary mirror.

4. Spectral range 340 to 1014 nm.

5. Diameter of smallest axial two-reflection ghost image approximately 48 mm. This involves the detector surface. Colour filters and detector windows may also produce ghosts.

6. If raytracing, include nominal colour filter of 3mm UBK7 at rear and place the focal surface .004 mm in front of paraxial focus at 486nm (to obtain the optimum focus).

7. Vignetting is shown in Fig. 3. Sample figures are:

Diameter (arc minutes)	Transmissison (per cent)
40	99
50	91
60	59

Appendix C. Two-prism image rotator

Optical dimensions in mm

Radius of curvature (positive concave to final image side)	Separation	Material	Clear diameter	Full diameter
- 21000.0*	- 8088.77	air	(4200)	
- 6230.9*	9985.77	air		
- 250.62	166.00	Homosil (Heraeus)	94	104
- 263.19	296.30	air	105	108
571.43	128.00	Homosil (Heraeus)	78	82
- 111.61	1.50	UBK7 (Schott)	70	74
854.25	302.82	air	70	74

Focal plane

Field of view	(unvignetted)	2.5 arc minutes diameter
	(partially vignetted)	5 arc minutes diameter

* See note 3

Notes to Appendix C

1. This table does not list silica/silica joins or plane reflections.

2. The separations shown are measured along the folded axis; see drawing for actual sizes of prisms.

3. Figures marked * refer to vertices of mirrors of Cassegrain telescope

4. Distortion ratio 1.0014 (pincushion) at ± 1.2 arc minutes.

5. Corrected for spectral range 300 to 1000 nm.

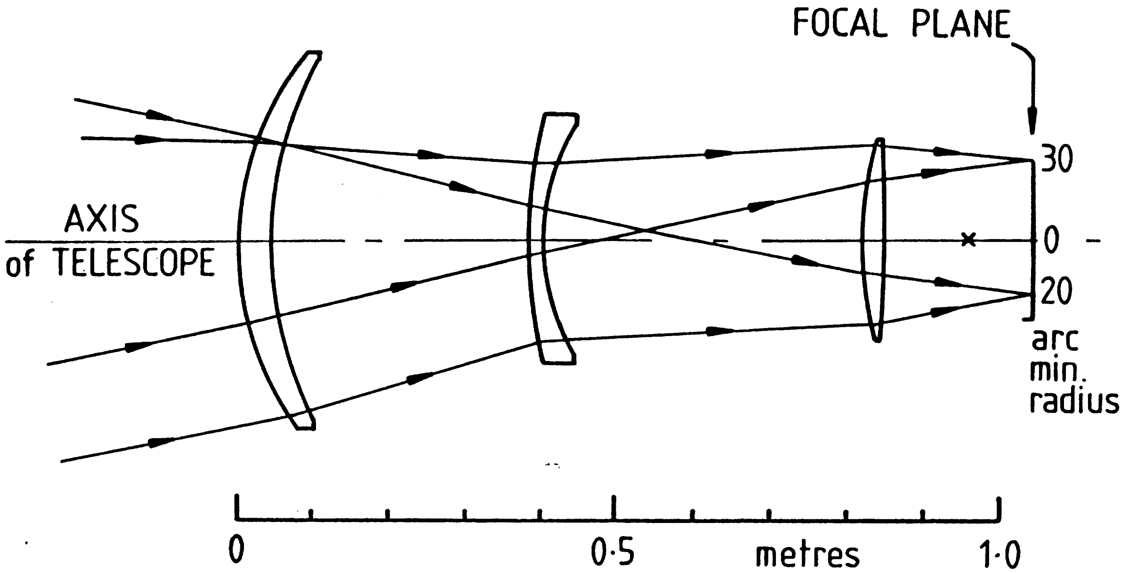
6. Equivalent focal length 47053 mm at 460 nm with nominal telescope mirrors.

7. Principal rays diverge by ± 0.056 degrees at ± 1.2 arc minutes.

8. Diameter of smallest axial two-reflection ghost image approximately 20 mm.

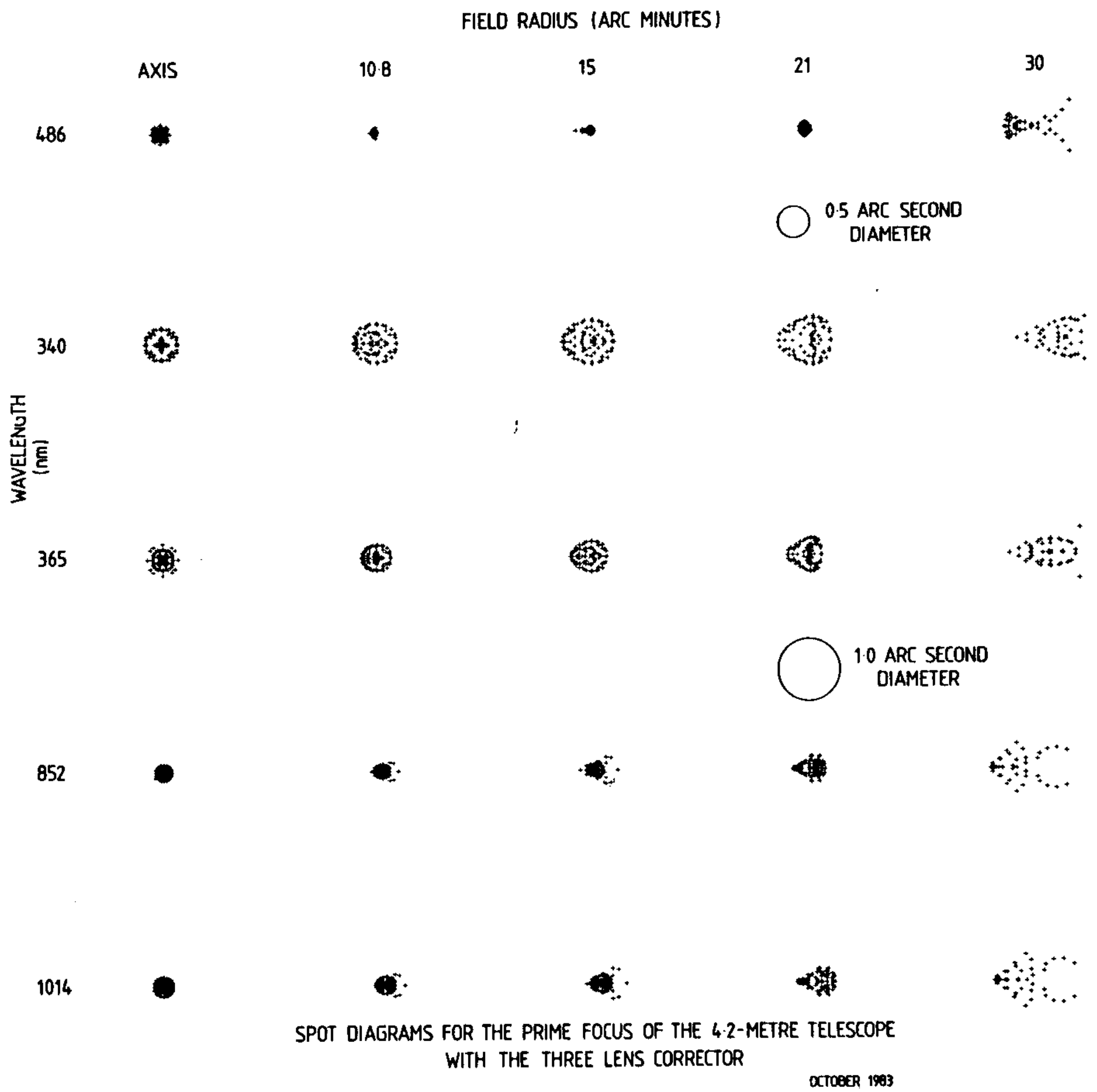
9. When raytracing, place focal surface 0.512 mm inside paraxial focus at 480 nm to obtain the optimum focus.

Figure 1



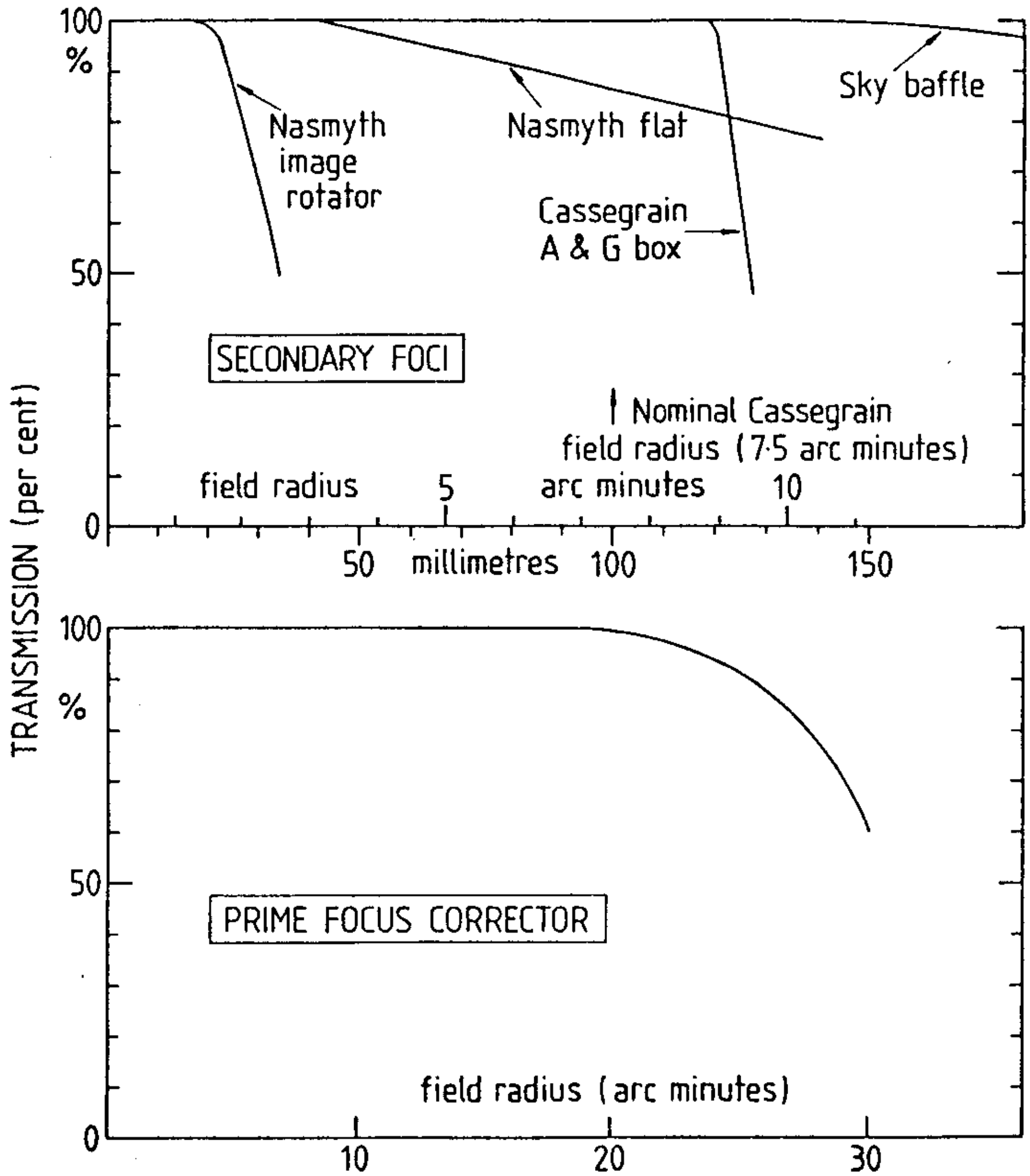
The three-lens prime-focus corrector of the 4.2-metre telescope. The front two elements are of UBK7 glass and the rear element is fused silica.

Figure 2



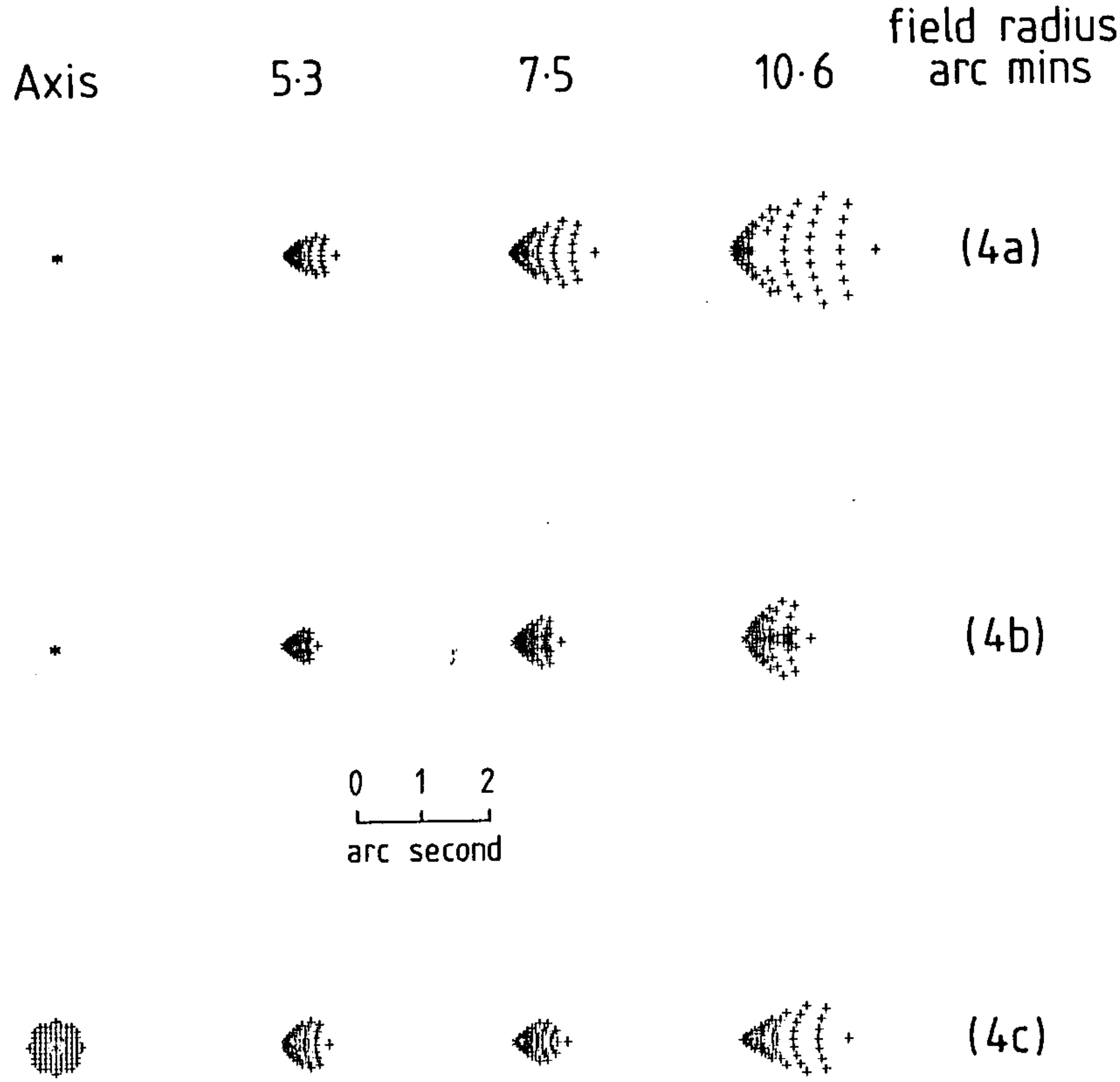
Spot diagrams for the 4.2-metre telescope with the prime-focus corrector. These show the theoretical geometrical aberrations in a single plane.

Figure 3



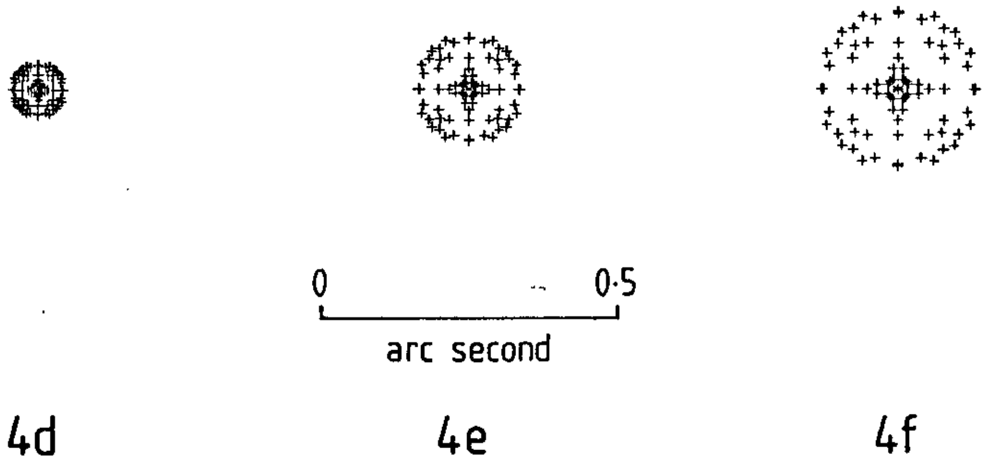
Vignetting at the various foci. The curves show the percentage transmission as a function of field radius. For accurate photometry, this should be used only with caution (see text). These curves refer to the area outside the constant central obstruction of 8.4 per cent (Table II) and supporting vanes obstructing 0.6 per cent.

Figure 4a, 4b, 4c



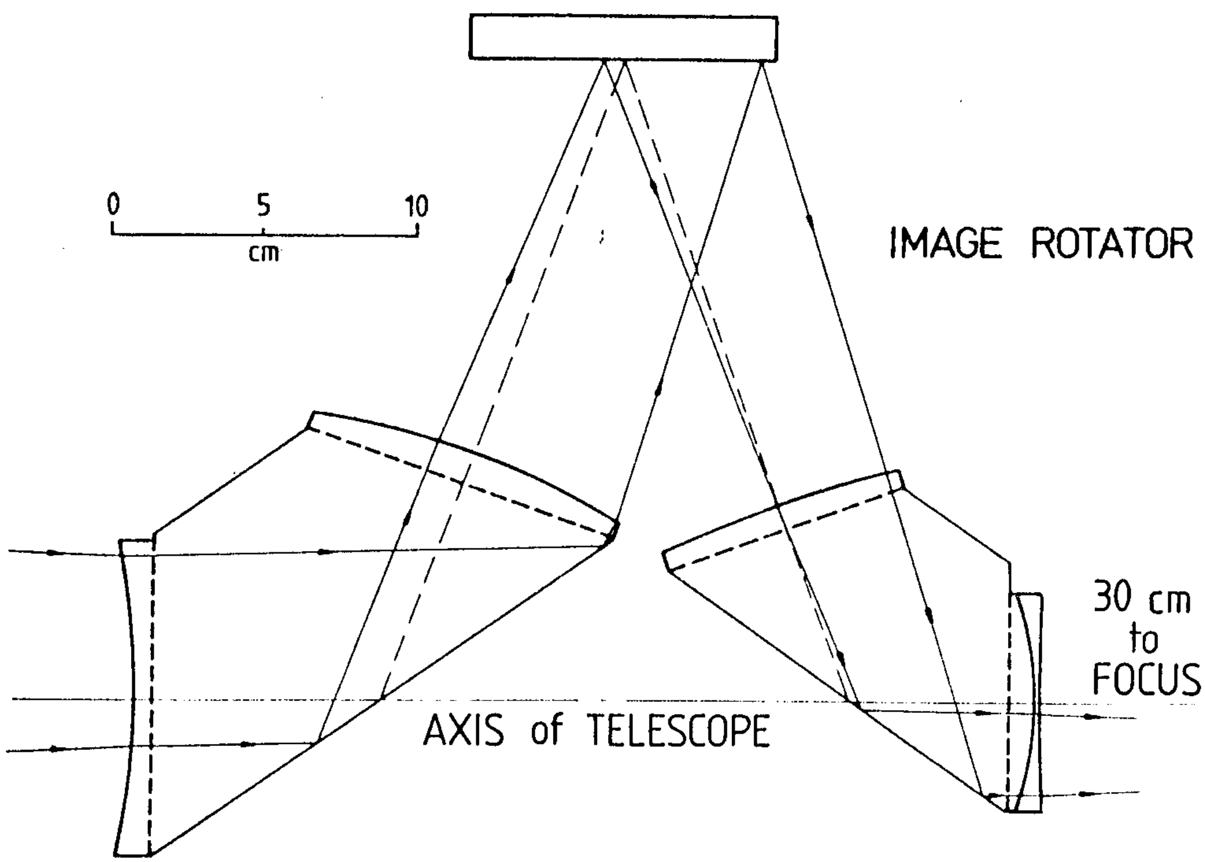
Spot diagrams at the f/11 foci. **4(a)** Aberrations on a flat focal surface passing through the nominal focus on axis. **4(b)** Aberrations on a curved surface (see text). **4(c)** Aberrations on a flat surface which is focussed for a compromise over the field. The nominal field radius is 7.5 arc minutes.

Figure 4d, 4e, 4f



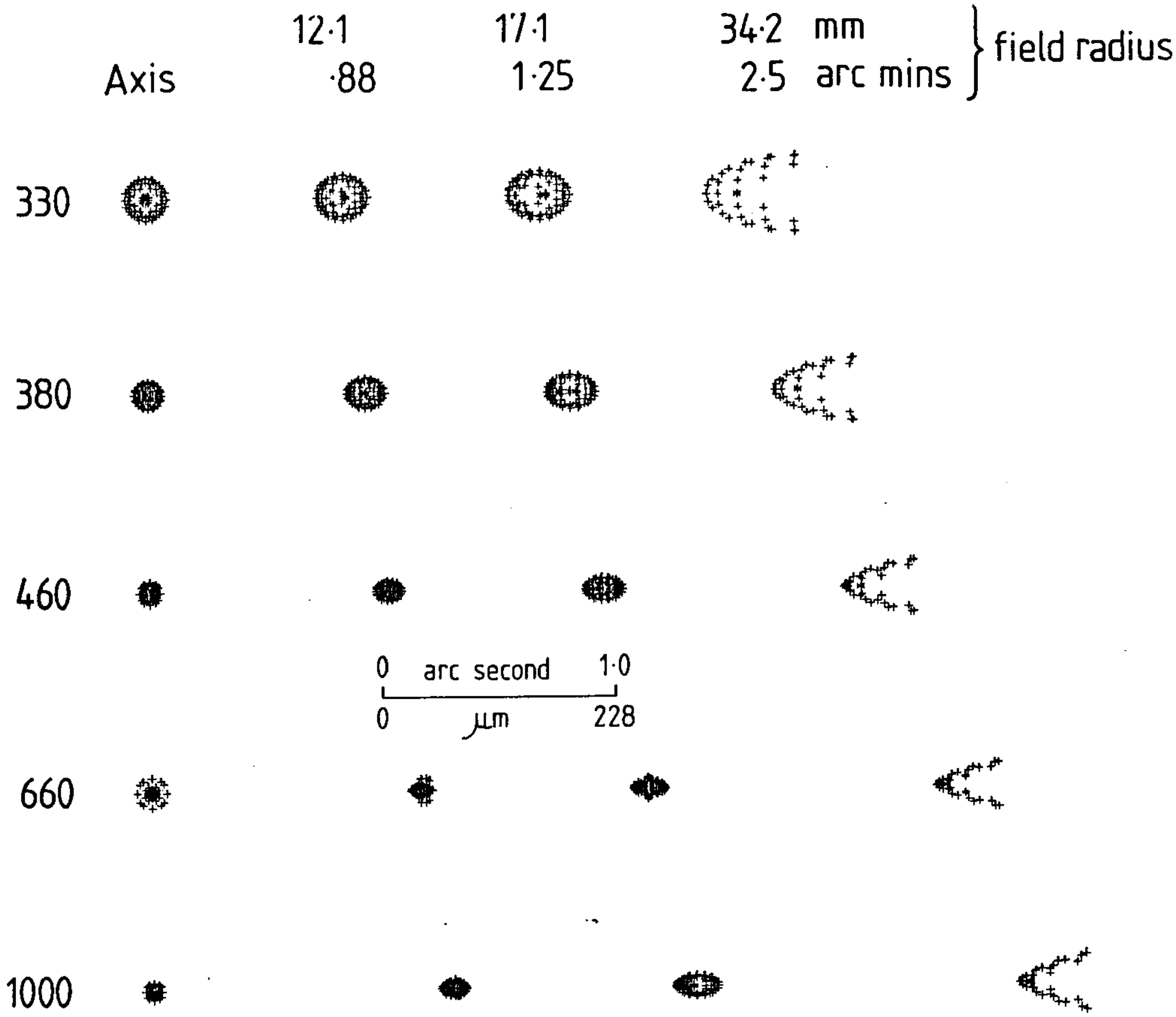
Images produced if the f/11 focus is moved outwards by 50, 100 and 150 mm. See also Table IIIa.

Figure 5



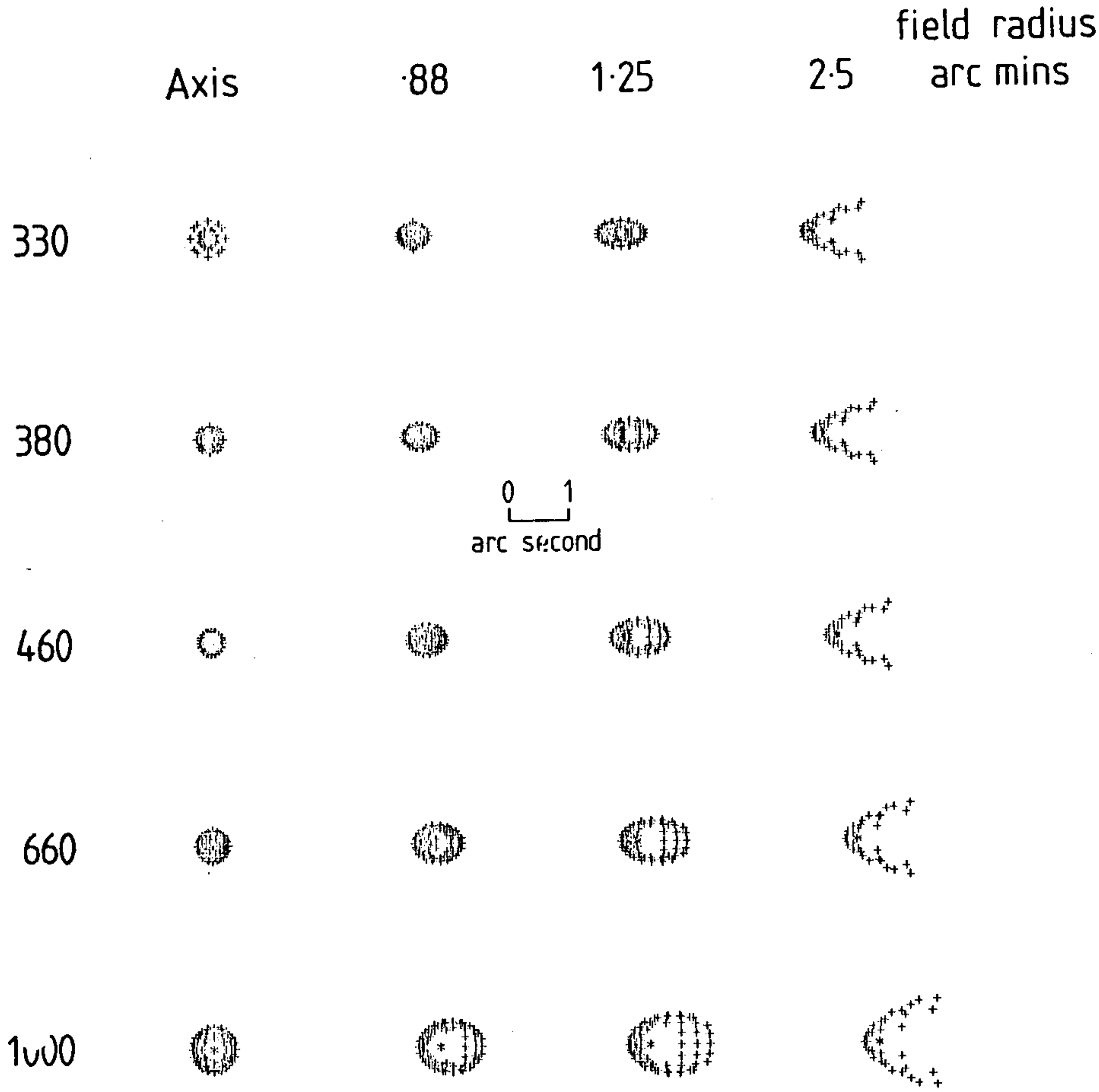
The Nasmyth image rotator

Figure 6a



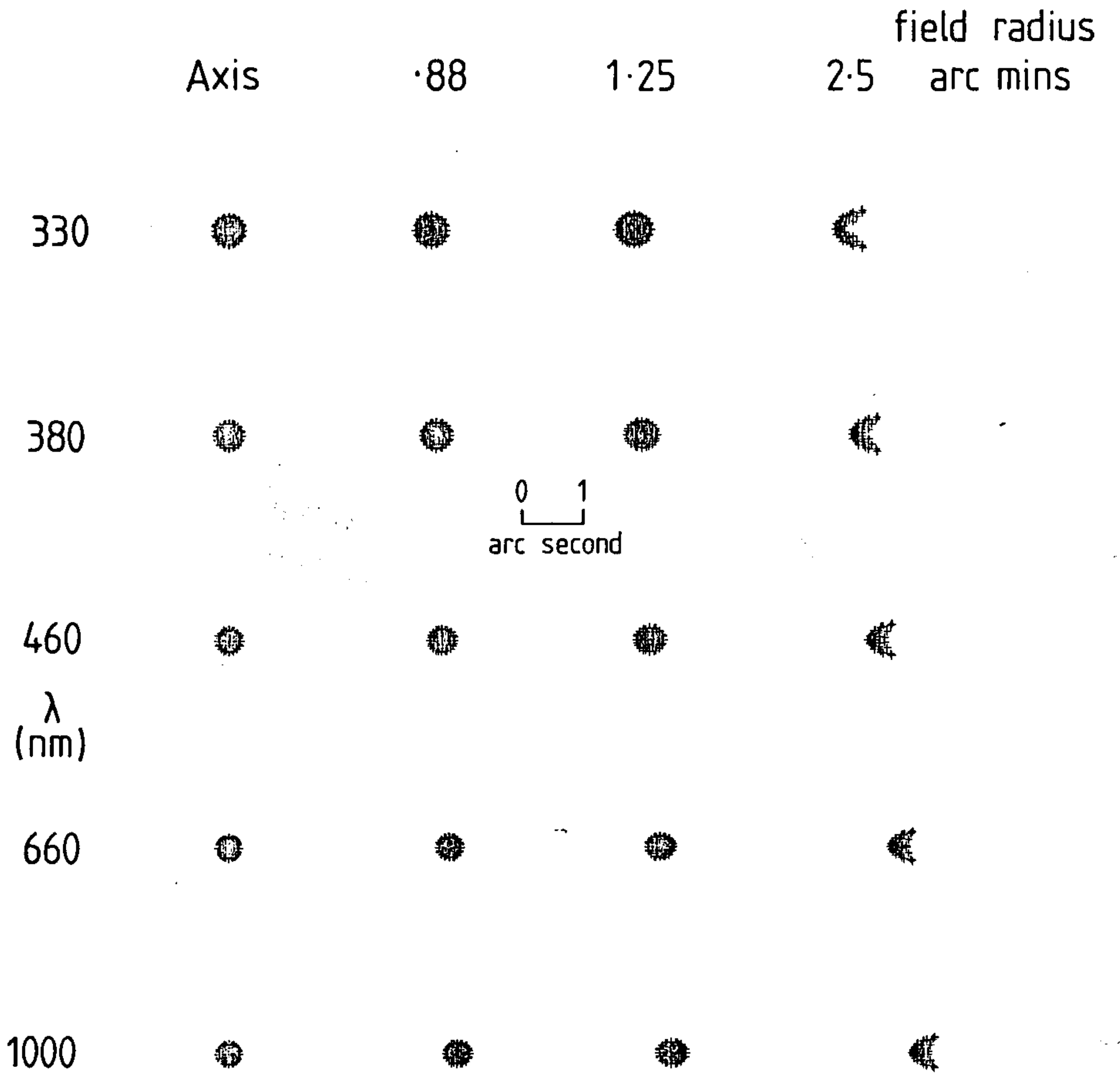
Spot diagrams in a single plane for the theoretical design of the Nasmyth image rotator. The designed field is 2.5 arc minutes in diameter, but the partially vignetted field out to 5 arc minutes diameter may be useful for guiding, etc. The diagrams show transverse chromatic aberration giving a slightly larger image scale at long wavelengths. If the images from 330 to 1000 nm are superimposed, this can make a line of about 0.7 x 0.2 arc seconds which will be radial and so in general have its long axis along the spectrograph slit.

Figure 6b



Spot diagrams for the image rotator degraded by refocussing with the secondary mirror to give additional back clearance (see Table IIIb and text).

Figure 6c



Spot diagrams for the image rotator degraded by moving the rotator and the final focus outwards by about 150 mm (see Table IIIB and text). The secondary mirror is optimally refocused.

Appendix D Optical diagram of the 4.2 metre Herschel Telescope