THE CATADIOPTRIC CAMERA AS USED FOR ASTRONOMICAL SPECTROSCOPY WITH IMAGE TUBES AND SIMILAR DETECTORS : A LIMITED REVIEW

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This paper compares the two major types of catadioptric camera, viz. the Maksutov camera and the Schmidt camera, when used for astronomical spectroscopy in instruments dedicated to image tubes, diode arrays and similar types of detectors. The review is limited to the detailed description of systems with which the author has been personally involved, that is, they have either been made at RGO or represent RGO participation in external projects.

Some other similar systems are referred to for comparison purposes.

INTRODUCTION

All cameras used in astronomical spectroscopy as the imaging systems in spectrometers are required to meet stringent specifications. Apart from the well known requirement that a camera should be fast enough to image the required entrance slit of the spectrometer into the minimum resolution element of the detector there are other, often less obvious, conditions to satisfy.

Some of these conditions, to ensure an efficient and acceptable system, are the following: (i) That the number of optical elements comprising the camera should be kept to a minimum to maximise throughput and cause the least amount of scattered light, (ii) The image quality should match the resolution of the best detector to be used, (iii) There should be sufficient aberrational balance to have good image quality when the system is working with an external aperture stop (the grating) whose aspect ratio can change depending on the grating configuration required by a particular central wavelength in a particular set up, (iv) Geometrical throughput should be as high as possible over the working range of grating attitudes.

When image tubes or similar detectors such as cryogenically cooled diode arrays are employed other constraints become relevant. One of these may be advantageous since most of these detectors are limited in size so the working field of view is reduced when compared with photo-

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graphic plate capabilities. Currently, the largest available image tube is the 8 cm McMullan Electronographic Camera first mentioned by McMullan, Powell and Curtis (1976), whereas one-dimensional diode arrays are typically 25 mm long and two dimensional arrays usually 1 cm or so square.

Other detector-related constraints may impose limitations on the camera design. All these detectors are currently flat in form so the camera is required to have a plane focal surface. The method of use often means that the detector, with ancillary equipment, is relatively large and can require cooling, so it cannot be put into the middle of the camera system. As a consequence of this, the plane focal surface must be freely accessible. In the case of 'folded' or Cassegrain type systems this must not be achieved at the expense of throughput due to obstruction in the camera.

Another constraint imposed on the modern camera system is that, due to the increasing use of cross-dispersion systems to give a larger spectral coverage over a small area field, the image quality must remain reasonably uniform over a full two-dimensional field. This last requirement puts more stringent limits on the state of the chromatic correction in the camera, chiefly, that there should be little longitudinal chromatic aberration to ensure all wavelengths focus in the same plane. For this two-dimensional application more than usual attention has to be paid to the transverse chromatic aberration as this is, effectively, a change of magnification with wavelength which could lead to a form of wavelength-related radial distortion.

Most cameras in use in recent years that form the catadioptric class are derivatives of the Maksutov and the Schmidt cameras. This paper is being restricted to cameras with which I have had some personal involvement. Most of the cameras described here were designed by Professor C.G. Wynne. My main contribution to such designs was the preparation of manufacturing specifications, acceptance testing and computer and experimental analysis of system performance.

There are no clear cut reasons as to why one type of system should be better than the other. As will be seen in the following discussion each type of system has its advantages and disadvantages which must be considered for each particular application.

MAKSUTOV TYPE CAMERAS

The first generation of spectrograph used at RGO dedicated to image tube detectors has been described by Palmer and Milsom (1972) and the collimator, grating, camera and detector layout is shown in Fig. 2 of Harmer's (1981) paper. This system employs a 14 cm focal length f/1.4 Cassegrain-Maksutov camera, the design philosophy of which has been published by Wynne (1971). The camera and spot diagrams are shown in Fig. 1. When this system was conceived it was expected to be used to record a one-dimensional spectrum only, so that the transverse colour inherent in the design (shown by lateral displacement in spot diagrams) is merely another term in the dispersion correction curve.

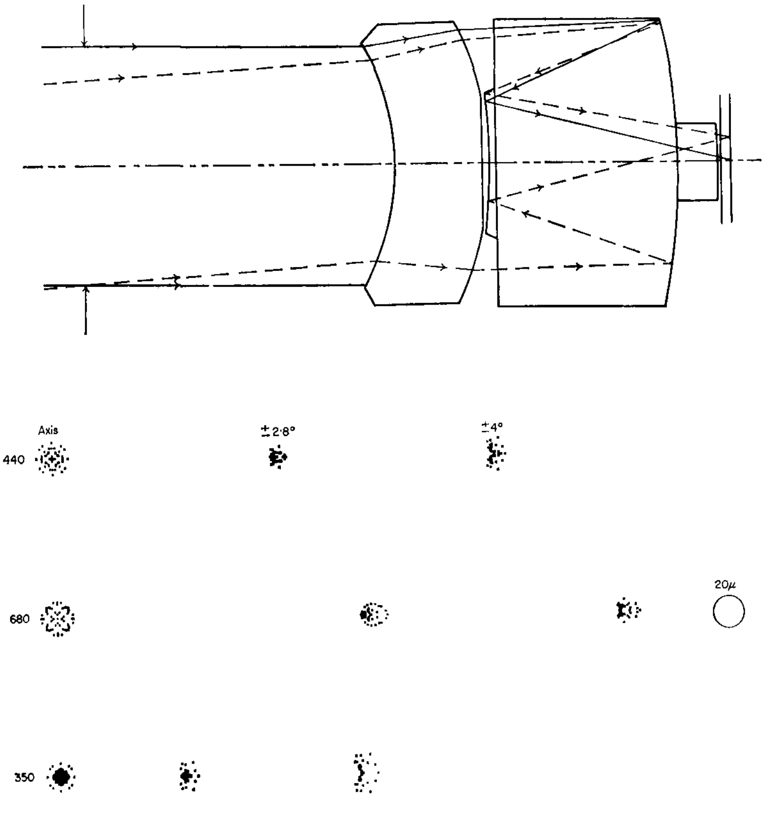

Fig. 1. The 14 cm, f/1.4 Cassegrain-Maksutov camera with its spot diagrams showing image spread on-axis and at obliquities of 2°.8 and 4° for wavelengths 440 nm, 680 nm and 350 nm.

After considerable use it was decided to extend the capabilities of this instrument by experimenting with using it at higher dispersions. In order to achieve this an holographic grating was made at the National Physical Laboratory by Dr M.C. Hutley. The grating has a sinusoidal groove form of frequency 2667 mm^{-1}. This enabled the spectrograph to give 1 nm mm^{-1} at 500 nm with almost uniform grating efficiency over 200 nm. The astronomical results were acceptably good but the scattered light component was higher than that expected from an holographic grating. Some of this was shown, by Harmer and Harmer (1978), to be due to the camera itself by measuring the photo-electric line profile under laboratory conditions. This profile is shown in Fig. 2 where it is interesting to note the quality of the actual image compared with the computed spot diagrams.

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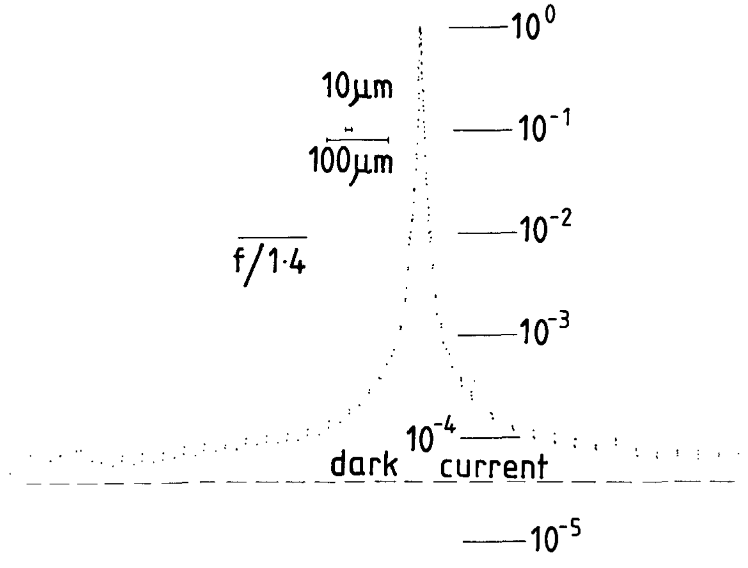

Fig. 2. Photoelectrically-measured line profile of f/1.4 Cassegrain-Maksutov camera. FWHM is about 3 µm, compared with total image spread of around 20 µm shown in Fig. 1.

As an adjunct to this grating investigation the effect of camera obstruction was computed since the holographic grating worked at much higher angles of incidence than used previously. Fig. 3 shows a pictorial representation of the obstruction offered by the camera secondary in comparison with the highest dispersion available for a standard grating; the light loss is considerable at these high angles of incidence and is worst at the centre of the field. Geometrical throughput deteriorates further at longer central wavelengths. In practice, however, the holographic grating was quite efficient, and at about 400 nm the measured difference in recorded spectra was comparable with that expected from the difference in dispersions. Spot diagrams have been computed through the system including the holographic grating, and the effect of compression of the beam due to grating attitude can be seen in Fig. 4. The geometrical image spread is much reduced in the direction of dispersion since, in this direction, the camera apparently works at a slower focal ratio.

With the addition of a field lens under the slit this instrument has been used successfully for long slit work by Boksenberg with the IPCS system. For this application a long slit is required to record star and sky spectra alternately and interchangeably so that necessary background subtraction can be achieved with acceptable photometric accuracy. With a long slit pupil imagery becomes very important to ensure consistent photometry throughout the instrument as described by Harmer (1974).

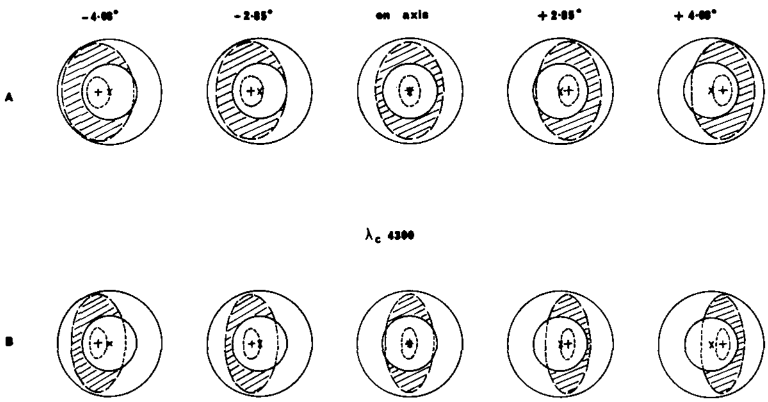

Fig. 3. Camera obstruction offered by f/1.4 Cassegrain-Maksutov system for two gratings set at central wavelength 430 nm. Diagram depicts telescope exit pupil in plane of camera secondary mirror along field of camera (in direction of dispersion). Shaded region is that part of telescope exit pupil passing camera obstruction. 'A' for 2nd order of grating of frequency 830.77/mm; 'B' for 1st order of holographic grating of frequency 2667/mm. X marks the centre of the system and + marks the centre of the beam.

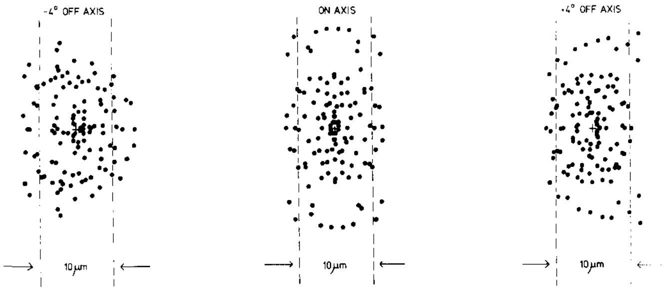

Fig. 4. Computed performance of entire spectrograph with f/1.4 camera and holographic grating, using geometrical ray trace. Compare spot sizes with those in Fig. 1.

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A further experiment with this camera being used in a 2-D mode has been described by Harmer (1981). For spectral coverage 350-750 nm the chromatic aberrations do not significantly affect the observations and data reduction processes.

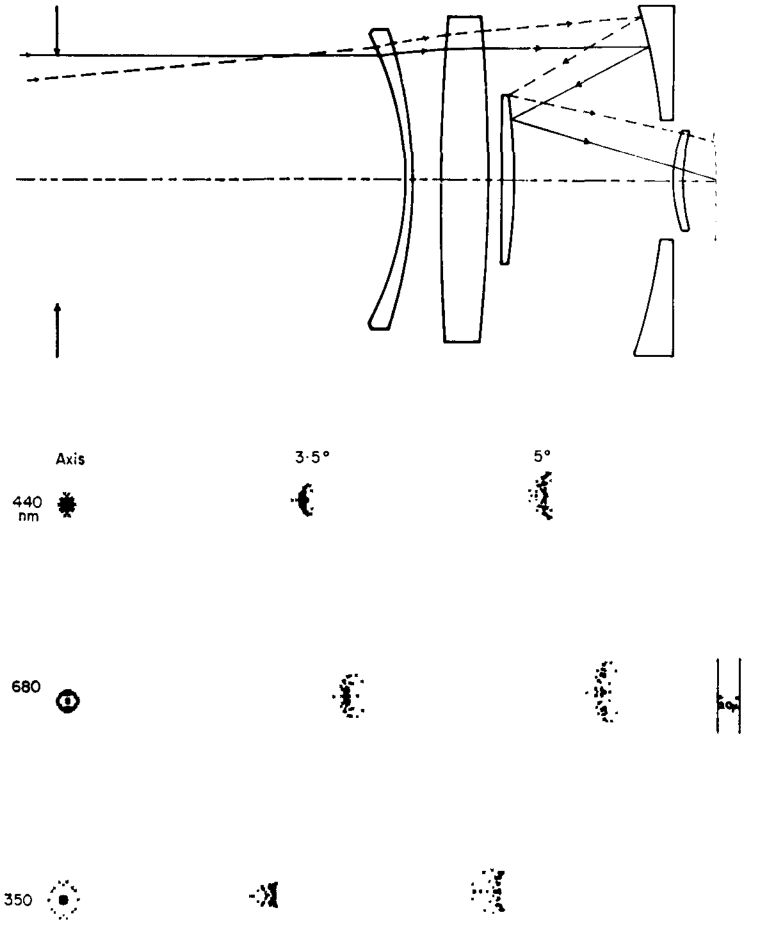

Fig. 5. The 25 cm, f/1.67 Cassegrain-Maksutov camera with its spot diagrams showing image spread on-axis and at obliquities of 3°.5 and 5° for wavelengths 440 nm, 680 nm and 350 nm.

The second type of camera that evolved from this was used in a spectrograph built at the RGO for use at the f/8 secondary focus of the AAT. A full description of the spectrograph is given by Palmer and Gietzen (1972) with details of the camera design having been published by Wynne (1972). The 25 cm focal length f/1.6 camera is a Cassegrain-Maksutov type having a two-element corrector instead of the more conventional single meniscus, see Fig. 5. In this case, the secondary mirror is elongated only in the direction of dispersion to give the required field coverage, and thus offers less obstruction than the circular secondary of the f/1.4 camera.

Later analysis showed the photoelectric line profile illustrated in Fig. 6 to indicate the image quality is better than the published spot diagrams suggest, these being shown in Fig. 5. It is worth noting, from this line profile, the reduction in the scattered light component compared to the slightly faster semi-solid system which has a long path length in fused silica. At the time that this and the f/1.4 system were built, the astronomical community was dubious about the efficacy and uniformity of broad band anti-reflection coatings, so none of the transmitting elements were coated. Some contribution to scattered light in the systems undoubtedly arises from these uncoated surfaces. Improvements in techniques and in the quality of the coatings themselves have encouraged astronomers to agree to their use in the present generation of camera systems. The f/1.6 camera has also been used in a cross-dispersed mode by Dickens, Carswell and others and produces satisfactory results.

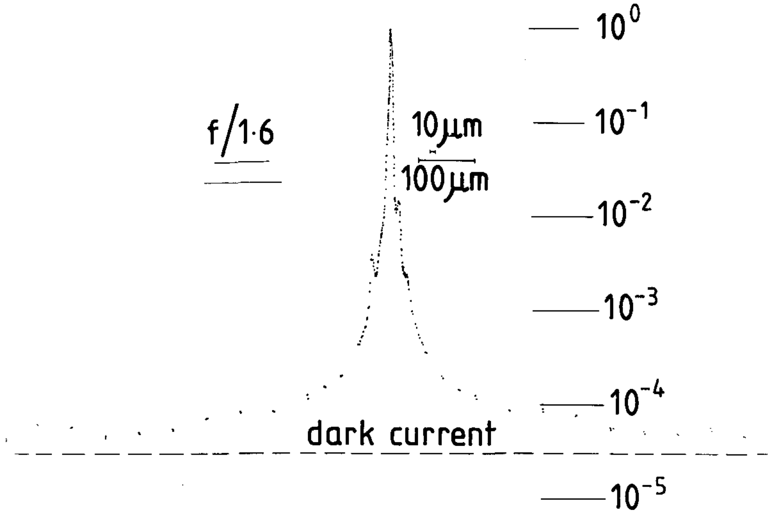

Fig. 6. Photoelectrically-measured line profile of f/1.67 Cassegrain-Maksutov camera. FWHM is about 3 μm, compared with total image spread of around 20 μm shown in Fig. 5.

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One way to overcome the obstruction introduced in the Cassegrain-Maksutov system has been to use only half a Maksutov camera. This is a reasonable solution, that may have limited two-dimensional capabilities, as demonstrated by Richardson & Brearly (1973).

A later system designed and tested at RGO is for use in a dedicated spectrometer using a Reticon one-dimensional diode array detector. The instrument is being constructed by Professor Blackwell at the University of Oxford to be used at the f/15 Cassegrain focus of the new LPO 1-m telescope.

Fig. 7 shows the general layout of the system. The diagram has been terminated at the first surface of the optical window in the system since this, with the following plano-convex field flattening lens, forms part of the evacuated cryogenic chamber housing the Reticon, details of which have not yet been finalised.

The camera has a nominal focal ratio of f/5.3 but is, in fact, part of an f/4 system of 27.3 cm focal length covering a field of 25 mm (length of the diode array). A computed spot diagram for a particular central wavelength is shown in Fig. 8(a). After manufacture this camera was laboratory tested using a 'star test'. The resulting on-axis image is shown in Fig. 8(b), the cross-lines being 10 μm apart. Allowing for some artificial image spread due to photography through a high power microscope the system is clearly up to theoretical expectations.

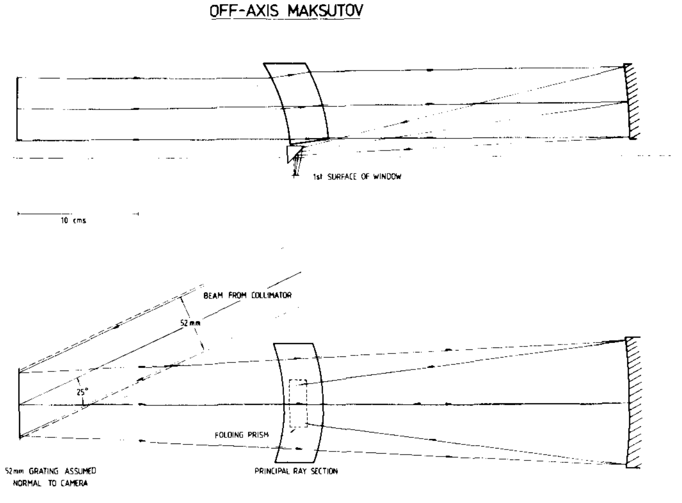

Fig. 7. 27.3 cm off-axis Maksutov camera for Oxford spectrometer.

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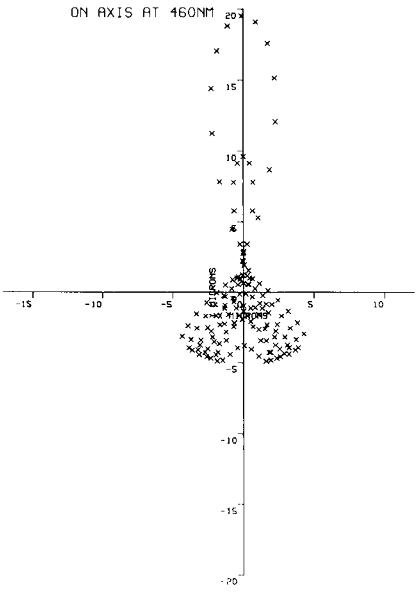

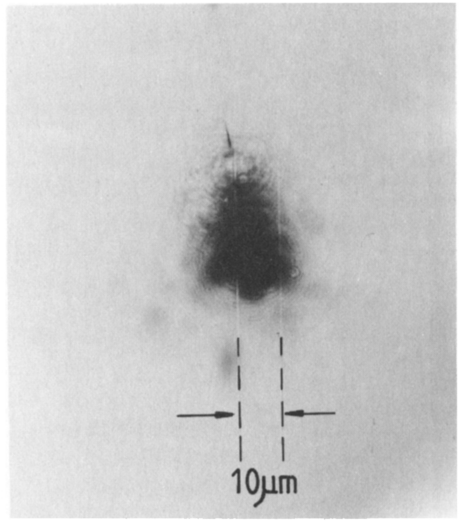

Fig. 8. (a) Spot diagram for off-axis Maksutov camera showing image spread on axis for wavelength 460 nm. (b) Laboratory image quality for off-axis Maksutov camera; the graticule lines are 10 μm apart.

SCHMIDT CAMERAS

The Schmidt camera has been used for astronomical spectroscopy for many years and its use with photographic plates is well known. One of the last spectrographs to be built at the RGO using classical Schmidt cameras and photographic plate as detector was that used at the Cassegrain focus of the Isaac Newton Telescope. It is a flat-bed instrument, mounted directly onto the back of the mirror cell and houses two conventional Schmidt cameras for intermediate dispersions and a semi-solid Schmidt camera for very low dispersions. Details of design and performance have been published by Harding and Candy (1971).

In this example the photographic plates are small, need no other extra equipment, and can, therefore, be placed in the centre of the system with minimal light loss due to obstruction. As previously stated, for image tubes and similar large detectors it is not possible to put these into the centre of the optical system with their ancillary equipment offering severe, often impossible, obstruction and heat convection problems.

If the Cassegrain type solution is considered a few viable systems may be found but, using the classical approach, this can lead to a camera that is physically rather long which may present problems in layout for the whole instrument. To illustrate this point Fig. 9 shows a Cassegrain-Schmidt and a Cassegrain-Maksutov of the same equivalent focal length.

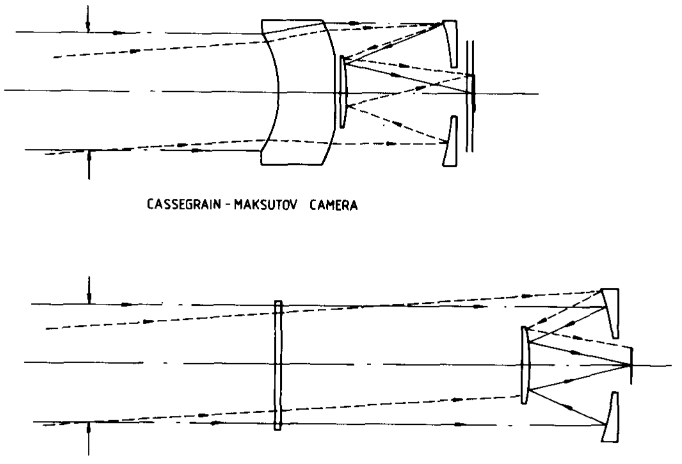

Fig. 9. Comparison of Cassegrain-Maksutov and Cassegrain-Schmidt cameras of the same equivalent focal length.

Other forms of folded Schmidt, including an off-axis folded system, have been described by Epps and Peters (1973). Standard Schmidt cameras with plane-mirror folding to make the focal surface accessible for large image tubes have been used in a number of working spectrographs, e.g. some Boller and Chivens systems, and the KPNO échelle spectrograph.

Some detector developments have meant the possible return of the large-field coudé spectrograph camera in a new rôle; to support a series of diode arrays set along the field. The Texas Reticon programme involves re-use of their "photographic" Schmidt camera system with tilting corrector plate, and the spectrograph on the RGO 30-inch coudé telescope (Harding, Palmer and Pope (1968)) houses an off-axis Schmidt camera with double-pass corrector plate, providing an unobstructed focal surface which could well be used in a similar way.

Another form of Schmidt camera developed for modern detectors is to make the detector an integral part of the image-forming system. Examples of this solution are to be found in the literature and are typified by those of Carruthers (1972) and Yarborough (1980). In the former, the focal surface of a classical Schmidt is a reflecting photocathode and the corrector plate is a pressure window so that the entire system can be evacuated to form a magnetically focussed image tube. The electron image is recorded through a hole in the camera mirror in a similar fashion to that employed by the McMullan electronographic camera. In the latter, the entire camera is made into an evacuated cryogenic chamber with a diode array placed in its flattened focal surface. A recent form of this dedicated camera/detector combination is being developed at RGO, with optical design by Wynne, and has been described by Murdin (1982, Fig. 2) at this colloquium. This type of integral Schmidt camera does satisfy most of the conditions except that, with the detector as part of the unit, some of the versatility of systems with accessible focal surfaces is lost.

Due to work by Wynne (1977) it is now possible to design Schmidt cameras somewhat shorter than the earlier classical form. The collimatorless dedicated camera/detector system mentioned above is one specialised example of this.

For more versatile astronomical spectroscopy a different type of system has been evolved in the form of a "folded" short Schmidt. Two such cameras have been made for a spectrograph constructed at RGO for use at the Cassegrain focus of the INT when it is installed at the new La Palma Observatory. The general form of the whole spectrograph is shown in the paper by Harmer (1982, Fig. 1) and has already been described at this meeting.

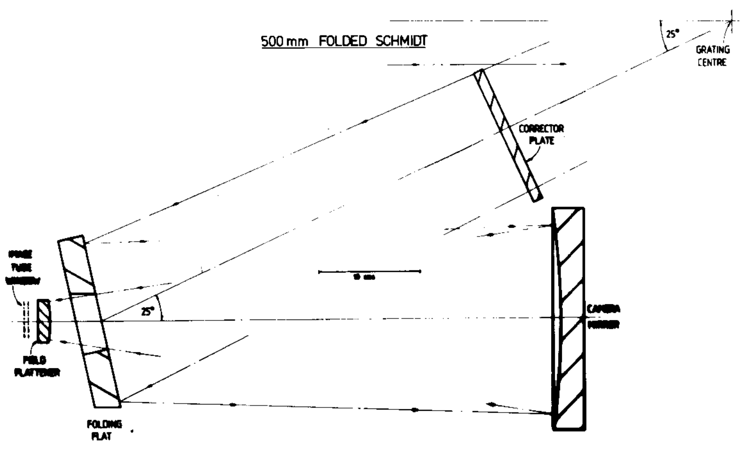

Fig. 10. 500 mm short folded Schmidt camera.

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This type of camera consists of a field flattened short Schmidt with a perforated folding flat between the corrector and the camera mirror, as shown for one of the above cameras of 500 mm focal length in Fig. 10.

By careful positioning of the folding flat and its 'angle of fold' the size of the hole can be adjusted to minimise obstruction to the incoming beam against giving a reasonable clearance for the focal surface to accept a number of different types of detector. Some care must be taken in designing the actual format of the folded systems since it may be possible for some of the incoming beam to pass through

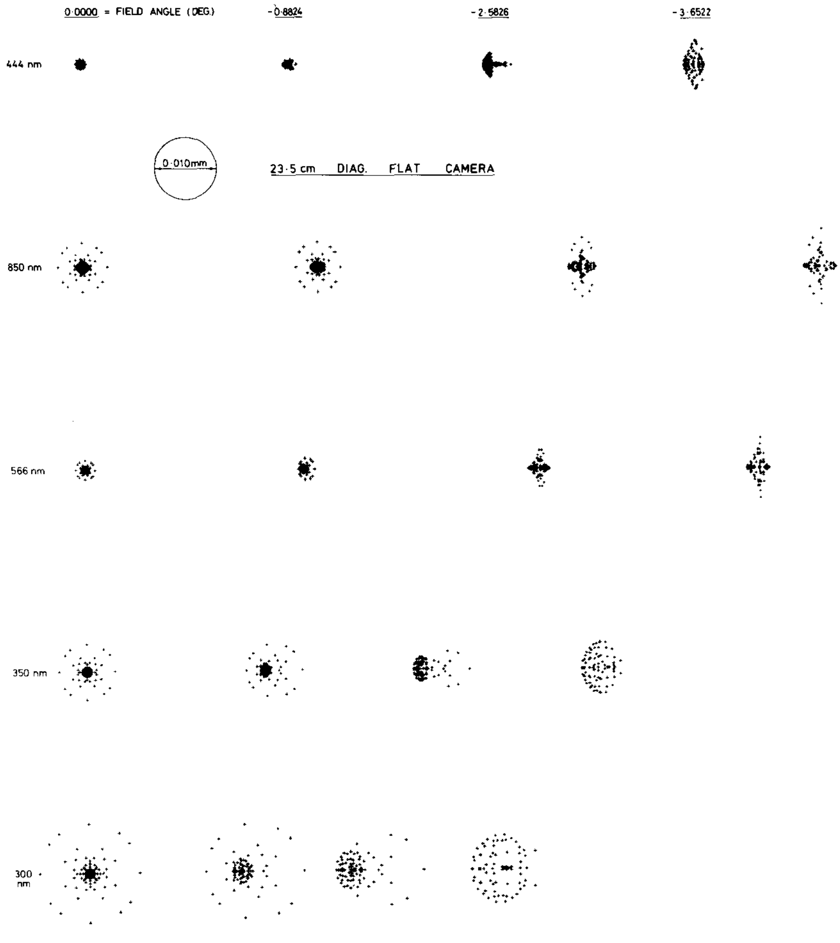

Fig. 11. Spot diagrams for 235 mm short folded Schmidt camera showing image spread on axis and at obliquities of 0°.88, 2°.58 and 3°.65 for wavelengths 444 nm, 850 nm, 566 nm, 350 nm and 300 nm.

the flat impinging directly on to the detector thereby causing an unfocussed stray light background. In this event, a simple plate baffle placed near the hole can be arranged to obstruct direct light reaching the detector without increasing the overall camera obstruction by a significant amount.

Figs. 11 and 12 show computed spot diagrams for the two systems constructed. Laboratory measurements and photographic tests performed by C.M. Lowne at RGO on these systems to date show their image quality is as predicted by theory, therefore, highly acceptable.

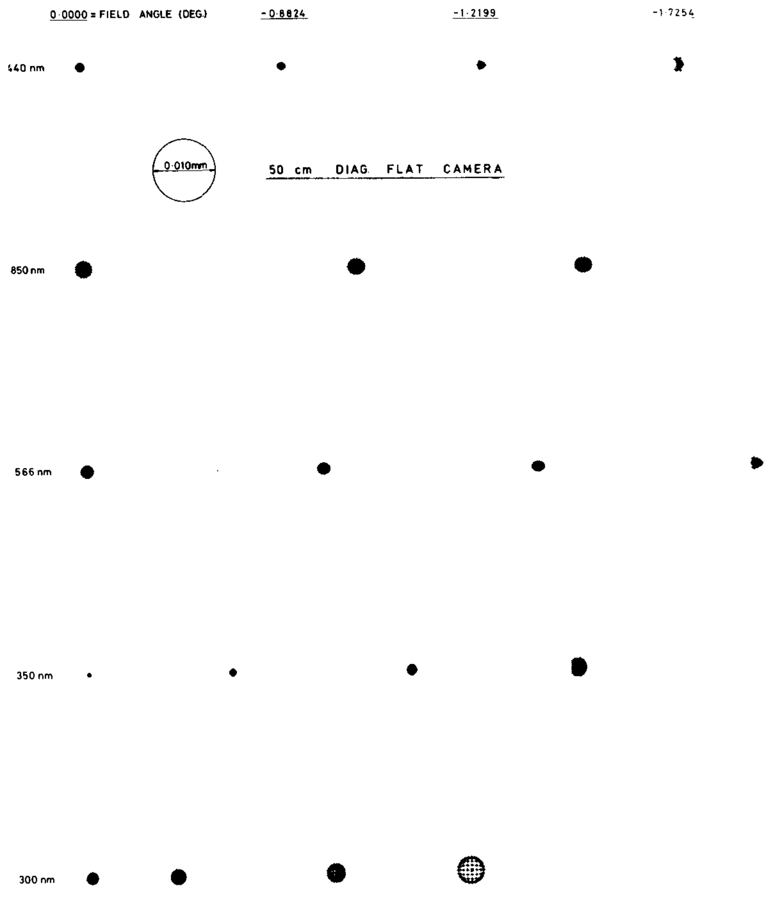

Fig. 12. Spot diagrams for 500 mm short folded Schmidt camera showing image spread on axis and at obliquities of 0°.88, 1°.22 and 1°.72 for wavelengths 440 nm, 850 nm, 566 nm, 350 nm and 300 nm.

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DISCUSSION

With greater emphasis on modern detectors the requirement for plane accessible focal surfaces is enhanced. Coupled with this is the need for high throughput, minimal chromatic aberrations and relatively compact systems.

In the foreseeable future the types of system most likely to receive attention are the short folded systems or the off-axis systems. In the latter case, it is likely that the two-dimensional capability will be limited. More work needs to be done to determine the potential of these off-axis systems. I have shown an example of an off-axis Maksutov camera, but off-axis Schmidt cameras exist, and it may be possible to design short ones. In this particular case the fact that the Schmidt requires an aspheric corrector could make the manufacture of part of such a corrector difficult and expensive (it is not unlikely that the whole corrector would have to be manufactured with the appropriate part being cut from it).

When deciding on the type of system most suited to one's needs the various attributes of each system must be considered. For example, it is known a Maksutov system is inclined to have more transverse chromatic aberration than a Schmidt. Alternatively, the Schmidt is inclined to have more sphero-chromatism than the Maksutov.

Such differences in controllable aberrations, together with versatility of operation, overall performance, throughput, scattered light properties, etc, including ease of manufacture, are some of the many parameters to be considered in making a selection. All these factors when coupled with the mechanical problems of available space, weight and rigidity, which may partly dictate the layout of the final instrument, merely make the choice of system less obvious. The question which must be answered is which system has the highest probability of performing the chosen task.

As I hope to have demonstrated, a great deal of work and consideration may be required before a reasonable solution is obtained. One of the major aids in assisting with a choice is to have the capability to perform a ray-trace analysis of the entire system so that some of its theoretical performance characteristics may be assessed. As a word of warning, however, geometrical ray tracing can never give a complete answer. Such properties as scattered light, diffraction effects due to overfilled gratings, grating defects, manufacturing defects, etc., are not so easily calculable. One has to rely on experience for the answer to some of these until the system is actually manufactured.

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