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Original Citation

Diego, F. and Walker, D.D. (1985) On the possibility of increasing the throughput of astronomical spectrographs by overfilling the dispersing element. Monthly Notices of the Royal Astronomical Society, 217. pp. 347-354. ISSN 0035-8711

This version is available at http://eprints.hud.ac.uk/30458/

Mon. Not. R. astr. Soc. (1985) **217**, 347–354

On the possibility of increasing the throughput of astronomical spectrographs by overfilling the dispersing element

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Accepted 1985 June 20. Received 1985 May 17; in original form 1984 December 6

Summary. This paper describes a technique which has been applied to the new AAT coudé échelle spectrograph, under construction at UCL, to increase its throughput without degrading resolution.

The effect of illuminating the slit with stellar images and extended objects is considered and a method of increasing the flexibility of the design is presented. The telescope focal ratio is modified by the addition of a lens in front of the slit. The degree of modification can be adjusted to optimize the spectrograph's light throughput under difficult seeing conditions or for different applications.

The technique may also be relevant to other spectrographs being designed and could even find applications in some existing instruments.

1 Introduction

The astronomical need for high-resolution spectroscopy of faint sources demands careful optimization of spectrograph light throughput. In many cases, the entrance slit is much narrower than the star image formed by the telescope, so most of the light is lost at the slit jaws.

Hence the throughput can be improved if the design allows a wider entrance slit whilst preserving resolution. This is the case if the spectrum format parameters (e.g. linear dispersion, projected slit, etc.) are conserved whilst increasing the overall demagnification factor of the spectrograph. This demands a longer collimator focal length and hence a larger monochromatic beam size.

Traditionally, most spectrographs have been designed so that the collimated beam just fills the dispersing element. The dimensions of this are normally decided not only by financial constraints but also by practical limitations such as instrument size and camera focal ratio. However, once the practical limit on disperser size has been reached, it is nevertheless still possible to increase the collimator focal length. The resulting collimated beam will then overfill the dispersing element. However, only an arc at the edge of the beam is lost whereas the slit dimensions change in direct proportion to the beam size. Hence, the light gained at the widened slit can more than compensate (Tull 1972).

If the slit width is not very small compared with the seeing profile of a star, the ideal beam size will be seeing-dependent. This is because in better seeing the light will be concentrated nearer the slit centre and the increase in slit width consequent upon enlarging the beam is then less advantageous. Thus, to optimize for an extended source demands the most overfilling and for a true point source, none at all. Further, if the slit is replaced by an image-slicer, essentially all the starlight is transmitted anyway. Then, providing that the length of the sliced image is not limited by, e.g. the need to avoid overlapping in a multi-order format, the advantage of overfilling disappears. In contrast, with a tightly packed échelle format, some of the overfilling will still gain light with an image slicer by virtue of the increased order separation projected on the sky. Fortunately, these contradictory requirements can all be met in one spectrograph by appropriately modifying the telescope focal ratio for specific applications.

The above ideas have been applied to the design of the new coudé échelle spectrograph for the Anglo–Australian Telescope and are relevant to other spectrographs.

2 Entrance slit illumination and grating overfilling losses

The fraction of the available light going through the slit depends on the energy distribution of the image formed at the telescope focus. An extended object illuminates the slit uniformly, so the throughput is proportional to the slit area. The case of stellar images requires a detailed study of energy distributions in seeing discs formed under various conditions.

2.1 INTENSITY PROFILES OF STAR IMAGES

The intensity profiles of star images have been extensively studied (Gyldenkaerne 1950; King 1971). Some of these studies utilize photometric and position measurements on photographic plates (Kormendy 1973; Auer & van Altena 1978; Green & Morril 1978; Schaefer 1981).

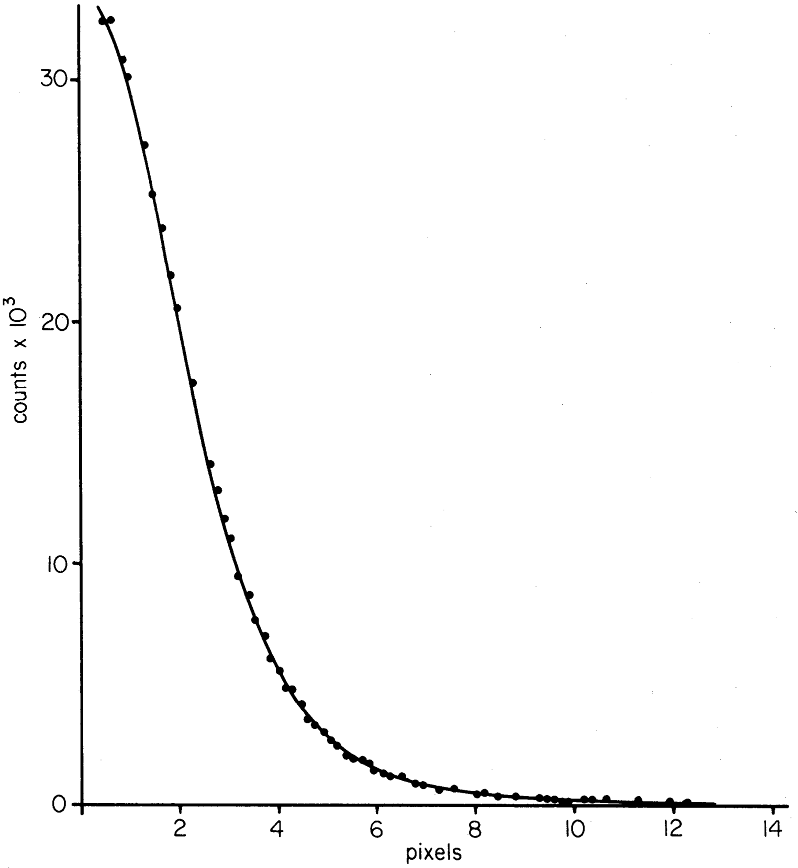

Figure 1. Typical example of a Lorentzian fitting to a CCD stellar image in intensity (counts) versus radial distance (0.4 arcsec pixels). Four stars taken from the same CCD frame were averaged before processing.

Also, the recent use of linear detectors (such as the CCD) for direct imaging has provided very accurate star profiles. Some of the images obtained during the commissioning of the UCL–CCD camera (Walker *et al.* 1985) were processed using GRASP (*G*iant *R*aster images *A*nd *S*tellar *P*hotometry) subroutines written by A. Penny (RGO) for the STARLINK system. GRASP mainly employs a Lorentzian (rather than Gaussian) model for the star profile and is currently used for photometric purposes (Walker 1984). Fig. 1 shows an example of a Lorentzian fitting to an average of four star images extracted from one of the CCD stellar fields. The images included in this study cover a range from 1 to 4 arcsec FWHM.

The Lorentzian parameters generated by the profile fittings have been used in a numerical model to integrate the energy distribution as a function of seeing. By this means, the throughput gains for slits corresponding to different collimator focal lengths (i.e. beam diameters) have been obtained. We plan to present a detailed analysis of star profiles and slit throughputs in a separate publication.

2.2 LIGHT LOSSES DUE TO OVERFILLING

The other half of the calculation – light lost by overfilling the disperser – is simple geometry. Fig. 2 shows a grating illuminated by three collimated beams of different sizes. The overfill losses (shaded areas) were calculated for several beam diameters and expressed as a fraction of the total area of the annular telescope pupil projected at the grating.

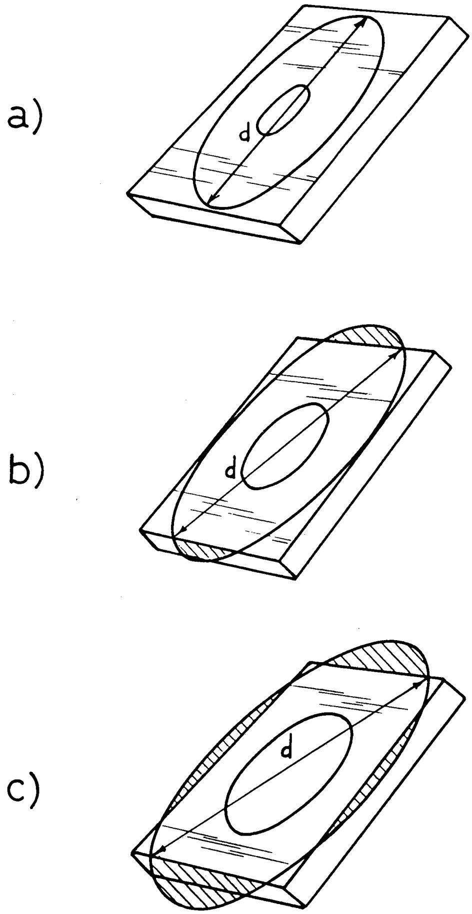

Figure 2. A grating is illuminated by different collimated beams. (a) The beam just fills the grating and the only light loss is that of the telescope secondary mirror shadow. (b) A larger beam overfills the grating length. (c) An even larger beam overfills the grating width as well. Note the increased size of the central shadow on the grating.

Note that the diffracted beams are limited by the grating dimensions, so a larger collimated beam implies a wider camera aperture only from the fact that the illuminated area on the grating is larger (i.e. increased *d* in Fig. 2). This may be troublesome in those spectrograph designs which demand very fast cameras, so any design arrived at in this way should be tested by raytracing.

3 Application to the AAT coudé échelle spectrograph

The gain from a wider slit, minus the loss due to overfilling, can (for appropriate applications) give a substantial overall throughput advantage. As an example, the coudé échelle spectrograph being developed at UCL for the AAT, has been designed in accordance with this idea. [Walker & Diego (1985) summarize the design of this instrument.]

The spectrograph has been optimized for the particular characteristics (e.g. spectral coverage, format and pixel dimensions) of the UCL–IPCS (Boksenberg 1972), although other small-format detectors such as CCDs will be accommodated. A primary aim is to cover a wide spectral range in a single exposure, and this implies that the échelle orders are tightly packed. The projected slit length is therefore limited by both the order separation and the finite detector pixel size. In this application, overfilling permits a slit that is longer as well as wider due to the changed demagnification factor and this gives a further throughput gain.

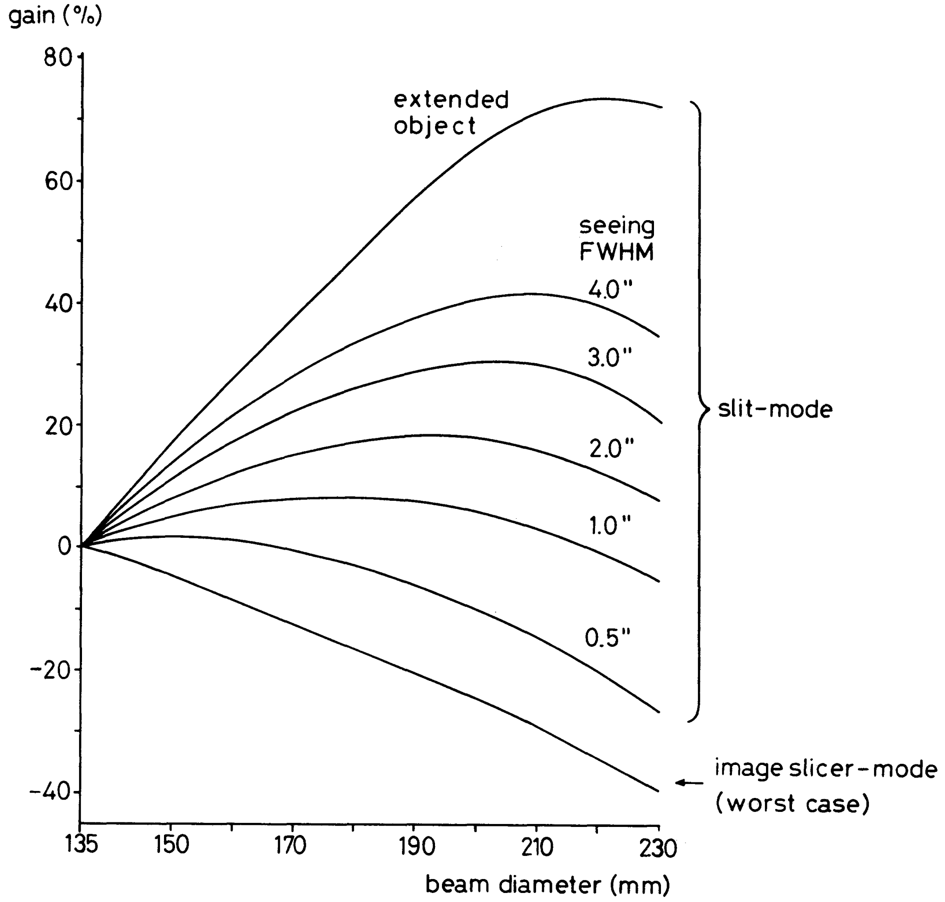

Figure 3. Net throughput gain for the AAT coudé échelle spectrograph for different beam sizes and seeing conditions. The abscissa represents the collimated beam diameter. The ordinate gives the gain relative to the throughput of a slit corresponding to a beam that just fills the échelle grating. The top curve shows the case of a uniformly illuminated slit and represents maximum overfilling gain. The lowest curve shows the maximum loss when an image slicer is used, i.e. when all the starlight enters the spectrograph.

The échelle will be a Bausch and Lomb $204\times408\,\mathrm{mm}^2$ ruling with a measured blaze angle of 64.6° (Loewen 1984, private communication). The grating will be mounted in-plane, facing-camera with a beam separation of 12°. It is then filled by a beam of 135.5 mm in diameter for which the corresponding entrance slit dimensions are: length=3.7 arcsec and width=0.48 arcsec. This width projects over two IPCS pixels.

The net throughput gain is plotted in Fig. 3 as a function of the beam diameter and different seeing conditions. The gains are relative (in per cent) to the throughput obtained with a beam just filling the échelle and the overfilling losses include a central obstruction of 37 per cent (in diameter) in the AAT beam. Note that the results presented include the effect of limited slit length, which is irrelevant in good seeing but important in very poor seeing or for extended sources. Thus in these later cases the overfilling gain would be somewhat reduced for single-order, long-slit work, e.g. when using an interference filter to select one order encompassing one spectral line of particular interest. In good seeing, the gain is maximized for a 175-mm beam, for which the slit dimensions are 4.7 × 0.62 arcsec. To optimize for poorer seeing demands a larger beam since the light is less concentrated and a larger slit area can be illuminated.

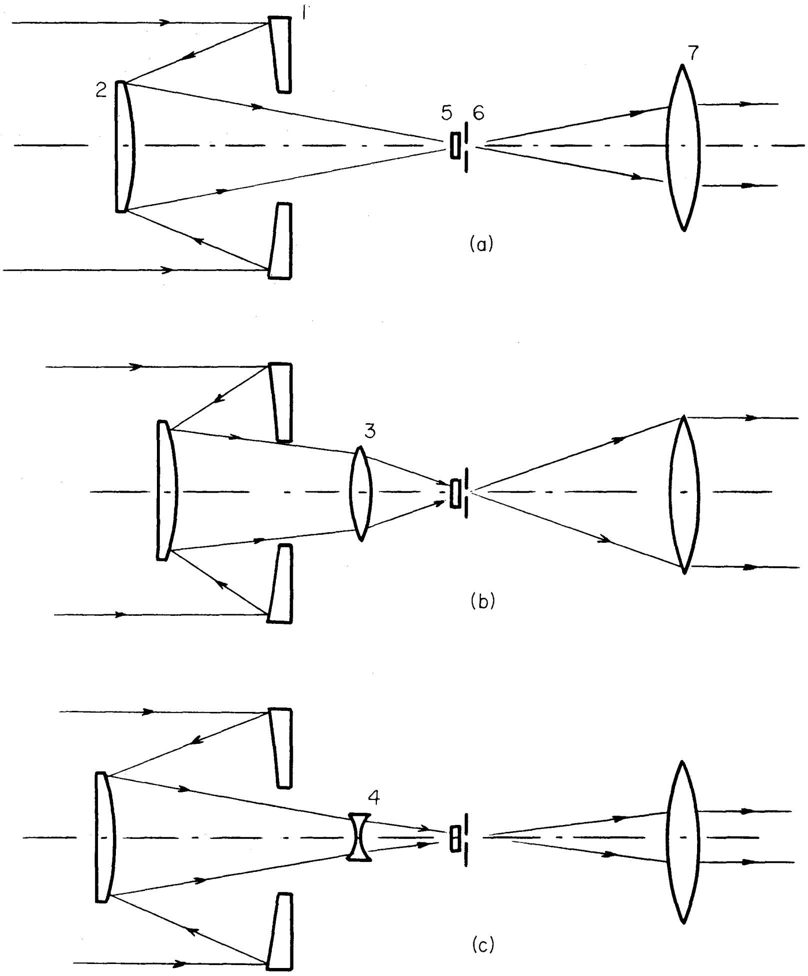

Figure 4. Focal modifier scheme used to provide different collimated beam sizes. (a) Unmodified system gives a basic collimated beam size. (b) Focal reduction by a positive lens produces an enlarged beam. (c) Focal increase by a negative lens reduces the beam size. The telescope must be re-focused and a field lens re-images the telescope pupil in each case. The scale of this drawing has been exaggerated for clarity. 1: Telescope primary mirror; 2: telescope secondary mirror, 3: focal reducer lens; 4: focal increaser lens; 5: field lens; 6: slit; 7: collimator.

The extreme case is an extended object, for which the optimum beam increases to 220 mm, even larger than the grating width, which is then overfilled in all four sides.

This spectrograph is intended to work also with image slicers with which some or all of the advantages of overfilling the grating are lost. Then the optimum beam size is that which just fills the échelle.

Thus the spectrograph would work optimally if the collimated beam size could vary from 135.5 to 220 mm in order to cover all possible conditions. Otherwise, losses could be substantial for those modes for which the collimator focal length was not optimum. A solution is to use collimators of different focal lengths for different applications, but this would create a considerable increase in cost and in control complexity.

A much simpler and practical alternative consists of a set of interchangeable focal modifiers inserted before or after the slit (Fig. 4). The AAT coudé beam is *f*:36 and if an intermediate value around 175 mm for the basic collimated beam diameter is chosen, the focal ratio would have to be increased to *f*:46 (beam size of 135.5) optimum for image slicer work or reduced to *f*:29 (beam size of 220 mm) optimum for extended object work. A lens before the slit will affect the plate scale of the telescope, so the entrance slit dimensions expressed in angular units on the sky will be modified but the projected values expressed in linear units will remain the same. The lens curvatures would be very small, so the chromatic aberration from even a singlet will be negligible. It is expected that there will be about three or four pairs of lenses (multicoated for blue and red wavelengths) mounted on a wheel and matched to interchangeable field lenses (located near the slit) in order to preserve pupil imagery (Harmer 1974).

Consequently, the spectrograph will be able to work under optimum conditions covering the range of beam diameters shown in Fig. 3 and also, overfilling will be reduced or absent when an image slicer mode is chosen, depending on the application.

The implications of these operating modes on the aperture of the 706-mm focus camera are shown in Fig. 5. The camera is a folded Schmidt and its focal length has been calculated so that the free spectral range of the longest wavelength order to which the IPCS is nominally sensitive fits across the useable photocathode area (Walker & Diego 1985).

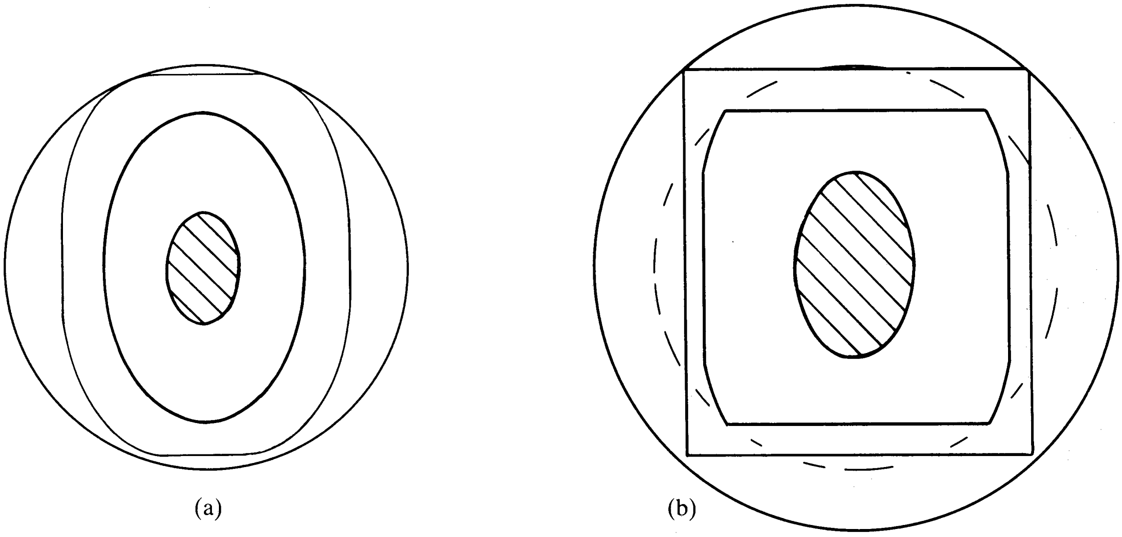

Figure 5. Polychromatic beam envelopes at the Schmidt corrector plate of the 706-mm camera of the AAT coudé échelle spectrograph. The envelopes correspond to the entire field of the camera. The camera aperture is represented by the large circumferences. (a) Is for a collimated beam diameter of 135.5 mm (i.e. no échelle overfill) and (b) is for a colllimated beam diameter of 220 mm (i.e. maximum échelle overfill). In this case, the envelope is approximately a square as the result of the échelle vignetting. The dotted line represents the camera aperture for a no-overfill condition.

When the collimated beam size is increased from 135.5 to 220 mm, the aperture of the camera's Schmidt corrector plate must be increased from 270 to 350 mm (i.e. the focal ratio changes from *f*:2.6 to *f*:2.0), in order to receive all the available light. However, if the aperture is kept at 270 mm, the throughput overfill gains are still preserved for the axial beam, but reduced by 8 per cent for the format corners.

The optical train of the entire telescope/spectrograph combination has been raytraced and the results are excellent.

4 Conclusion

The overfilling technique described provides a very useful way to improve the general efficiency of a versatile spectrograph, once the parameters of the main disperser have been set. For the case presented, the gains in light throughput (for a given resolution) range from 8 per cent for stars in good seeing to 74 per cent for extended objects.

The use of focal modifiers can be extended to cassegrain spectrographs, so the usual restrictions on collimator focal length can be avoided. Even existing spectrographs can be adapted in this way in order to obtain some of the advantages of the overfilling technique. Note however, that there may be limitations in spectrographs with very fast cameras, such as the AAT coudé échelle spectrograph operating with the enhanced throughput mode (Walker & Diego 1984, 1985). The optical complexity of the modifiers will increase for faster beams and/or larger modifications, so compromises could arise.

It is important to remember that in some cases, the overfilling technique may imply very wide slits, which combined with good seeing conditions, may be troublesome if the spectral resolution element then tends to be defined by the star image rather than the slit. The effect of image motion due to poor guiding will degrade the line profile and also create apparent wavelength shifts (Bingham 1979). For the AAT spectrograph under good seeing, the slit width is increased from 0.48 to 0.62 arcsec, well below the size of the best expected star image, so in this case the effect will be negligible.

Acknowledgments

We are grateful to Richard G. Bingham and the referee for their comments on the manuscript. FD acknowledges the receipt of a postgraduate scholarship from the Universidad Nacional Autónoma de México. DDW thanks the AAO for supporting this work.

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Note added in proof: Since submitting this paper, the overfilling concept has also been applied to the William Herschel Telescope échelle spectrograph (see Walker & Diego 1985).