THE NEW COUDÉ ÉCHELLE SPECTROGRAPH FOR THE ANGLO AUSTRALIAN TELESCOPE

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1. INTRODUCTION

During 1983, the advisory committee for instrumentation at the Anglo Australian Telescope (AAT) recommended that, as a matter of high priority, an échelle spectrograph should be procured for the f/36 coudé focus. The aim was to satisfy the high spectral-resolution needs of the community which, hereto, have been neglected. We at University College London (UCL) were invited to consider the design and our proposal was subsequently accepted by the Board. We are now at an advanced stage in optimizing the optical system, and mechanical design is proceeding. We plan to test the complete system in the laboratory at UCL prior to installation and commissioning at the AAT which we anticipate will be during 1987.

This paper is intended as a general introduction to the design philosophy of the instrument, paying particular attention to the properties of the detectors with which it will be used. Some implications on the requirements for similar instruments at future very large telescopes are also discussed.

2. INITIAL SPECIFICATION

The primary goal is to provide a spectrum with a wide wavelength coverage in a single exposure and with a resolution of at least $\lambda/\Delta\lambda = 50{,}000$ (as defined by the projected slit). This resolution is a good compromise with limiting magnitude. There is a further requirement for an enhanced throughput mode (at the expense of reduced resolution); higher resolution modes are also being considered. The instrument is being optimized for the properties of the UCL Image Photon Counting System (IPCS; Boksenberg, 1972) as primary detector, but the importance of accommodating other detectors, particularly CCD's is recognised.

As a common-user system, the instrument needs to cater for a wide range of astronomical problems, including abundance determinations, interstellar and emission-nebulae studies. This last implies the need for the provision of a moderate slit length to give spacial resolution, although the lack of a strong continuum implies that overlapping orders in this mode can be tolerated. The enhanced throughput mode, with its greater limiting magnitude, is primarily aimed at extragalactic observations of, for example, active galaxies and quasars.

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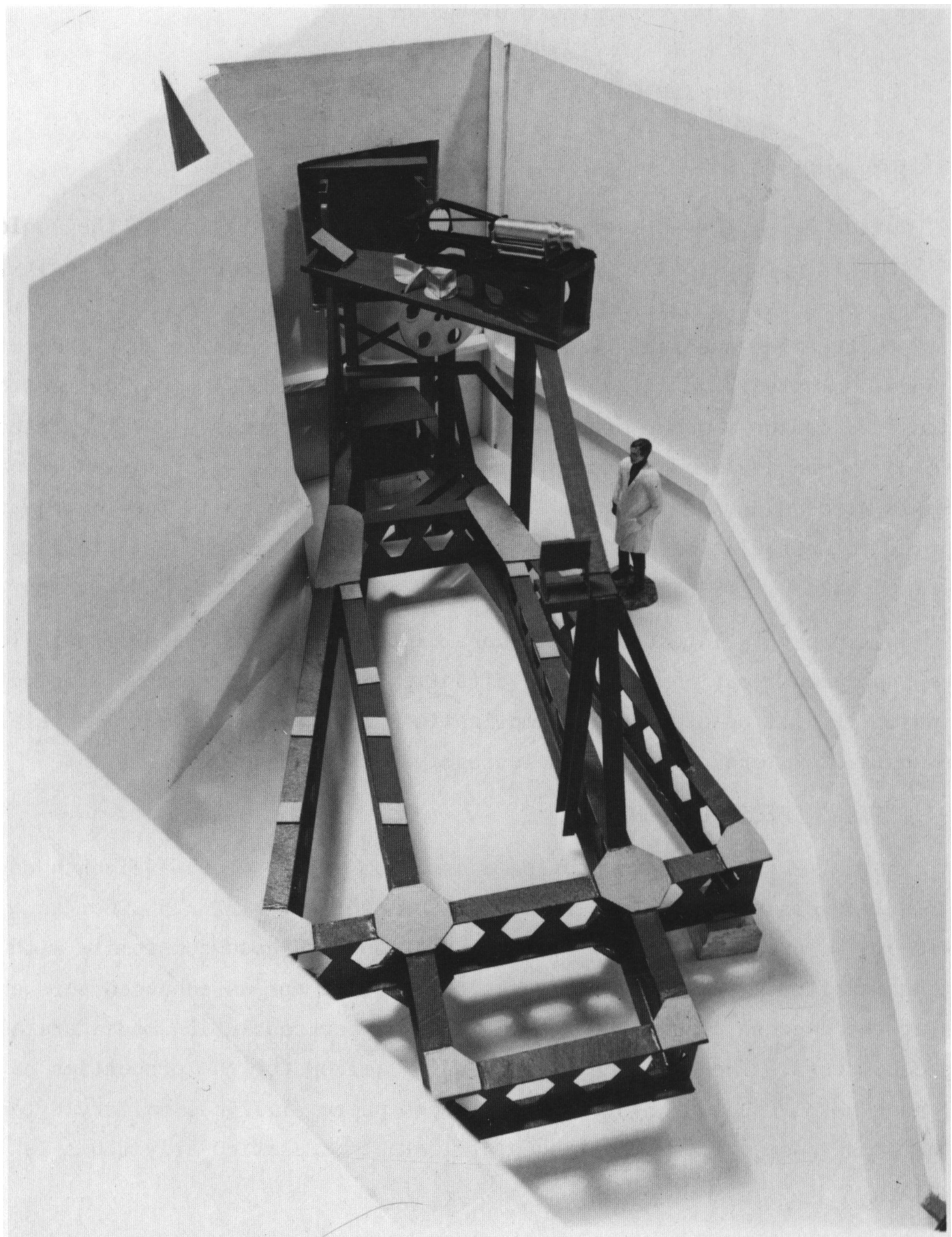

Scale Model of AAT Coudé Échelle Spectrograph, Viewed Looking Towards Slit Area. (Note that The base-frame already exists).

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The overall wavelength coverage of the spectrograph is to extend from the atmospheric limit near 3000Å to the CCD cut-off around 1.1μm. The UV end presents technical problems but was regarded as imperative for astronomical reasons. For example there is a NaI interstellar line at 3303Å. This line is important because, unlike the 5890-6Å doublet, it is unsaturated and is thus particularly useful for determining the Na column density. In extra-galactic studies, the UV is also often of prime importance, for instance in unravelling the forest of absorption lines associated with Lyman alpha in high redshift quasars.

3. DESIGN PHILOSOPHY

The spectrograph will be used with an IPCS format of 30mm x 16mm corresponding to either 2048 x 128 pixels of 15μm x 125 μm or 2048 x 255 pixels of 15μm x 63μm. The following primary design-considerations concern matching the two-dimensional spectrum-format to the major properties of the IPCS. With this detector, frame-rate and coincidence-loss factors limit the pixel-capacity to the values given above.

a) The free spectral range (FSR) at the nominal longest wavelength to which the detector is sensitive, should just fit over the useful width of the detective area. This ensures continuity of wavelength coverage in an exposure. For the IPCS, the condition is that the FSR at 7000Å subtends about 30mm.

b) The projected slit width should be sampled by two pixels with the detector working at its optimum resolution. This indicates a 30μm projected slit with the IPCS.

c) The intensity variations across the format should take account of the detector dynamic range. This is particularly important for photon-counting detectors which suffer coincidence losses, and it is considered further in Section 5.

d) The inter-order separation should be adequately sampled by the pixel size in the cross dispersion direction. For the maximum total number of pixels available with a given detector, and for particular inter-order separations, this factor influences the proportion of the total spectrum that can be recorded in a single exposure.

Other design aspects include the optimum choice of beam diameter for a given échelle size, adequate selection of camera characteristics, overcoating of all optical surfaces and minimization of scattered and stray light. Some aspects of ancillary facilities and control are also considered.

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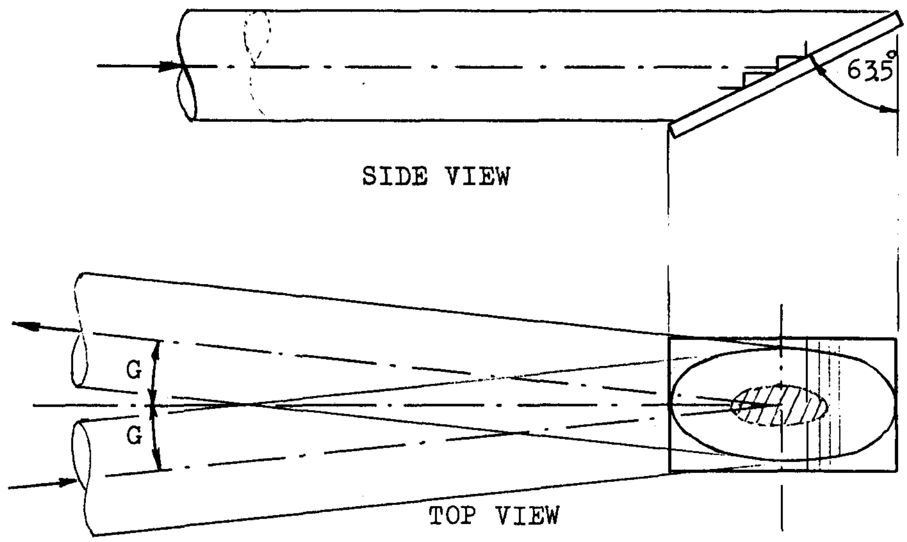
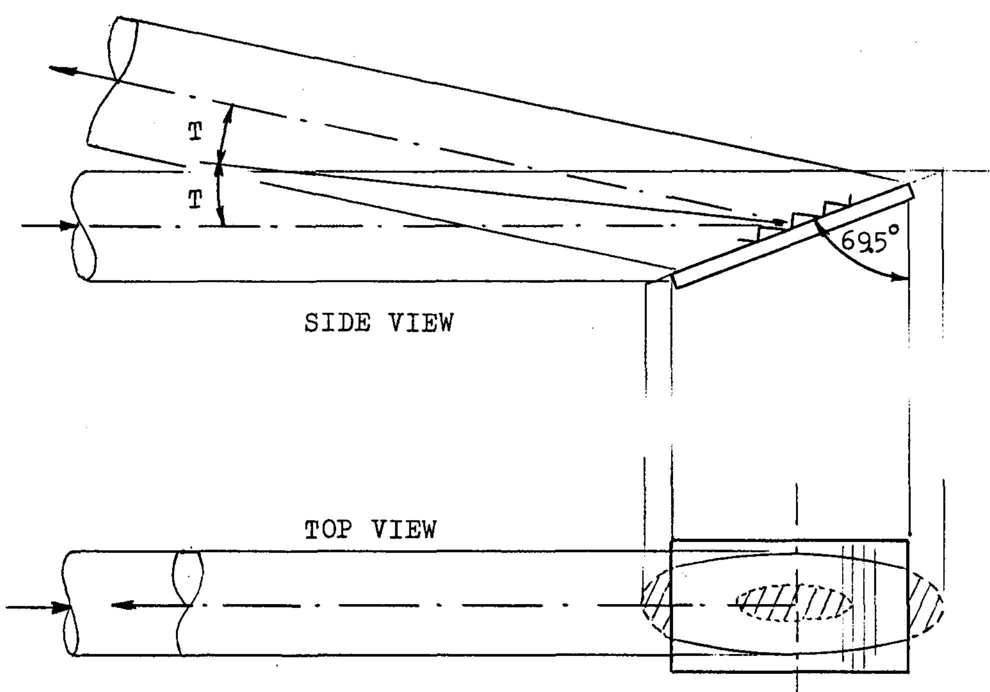
Figure 1



a) Echelle grating in QUASI LITTROW mount
(in TRUE LITTROW mount G = 0°)



b) Echelle grating in CONVENTIONAL ('in plane') mount
for T = 6° and beam overfilling the echelle

4. ÉCHELLE GRATING PARAMETERS

In the context of an échelle with constant blaze angle, the ruling frequency affects not the dispersion, but instead both the angular and spectral extents of the free spectral ranges. Thus, by combining cameras of different focal lengths with appropriately scaled rulings, different configurations may be obtained which satisfy the requirements a) and b) of section 3.

The characteristics of available échelle gratings (Bausch & Lomb) led us to choose a 204mm x 408mm grating blazed at 63.4^{o} (nominal) for which only two rulings are available:

- 31.6 g/mm with a long (∿700mm F.L.) camera gives a high resolution mode ($\lambda/\Delta\lambda$ = 80,000).
- 79 g/mm with a short (∿300mm F.L.) camera gives the enhanced throughput mode ($\lambda/\Delta\lambda$ = 32,000).

If the beam fills the length of the échelle, the corresponding slit widths would be 0.48 arcsecs and 1.2 arcsecs respectively. The exact beam size and camera focal lengths are dependent upon the échelle configuration (see sections 5 and 7).

Unfortunately, with a very long camera ($\lambda/\Delta\lambda$ >> 80,000) there is no practical solution which fulfills the condition of point a), since an échelle grating with ruling coarser than 31.6 g/mm is not yet available. Hence, in order to have a complete spectral coverage, it will be necessary to scan along the orders by rotating the échelle grating in its dispersion direction.

5. ECHELLE CONFIGURATION

There are two basic configurations that have been used in existing échelle spectrographs: In-Plane and Littrow (see figure 1). Both have little effect on the matching of the spectrum format geometry to the detector, but the choice is strongly influenced by the échelle efficiency and its variation along the orders (i.e. the blaze profile).

A detailed study of blaze profiles for different échelle configurations (Walker and Diego, in preparation), based on calculations by Schroeder and Hilliard (1980), shows that the In-Plane configuration confers some advantages over Littrow (see figure 2). The former is more uniform, so it is easier to assemble a final composite spectrum by calibrating and overlapping adjacent orders. Moreover, the In-Plane profile, despite its poorer peak and average efficiency, is superior to Littrow at the order ends where the efficiency is lowest. This is beneficial since in many applications it is the worst signal to noise ratio (SNR) in the final spectrum, not average or peak, that determines

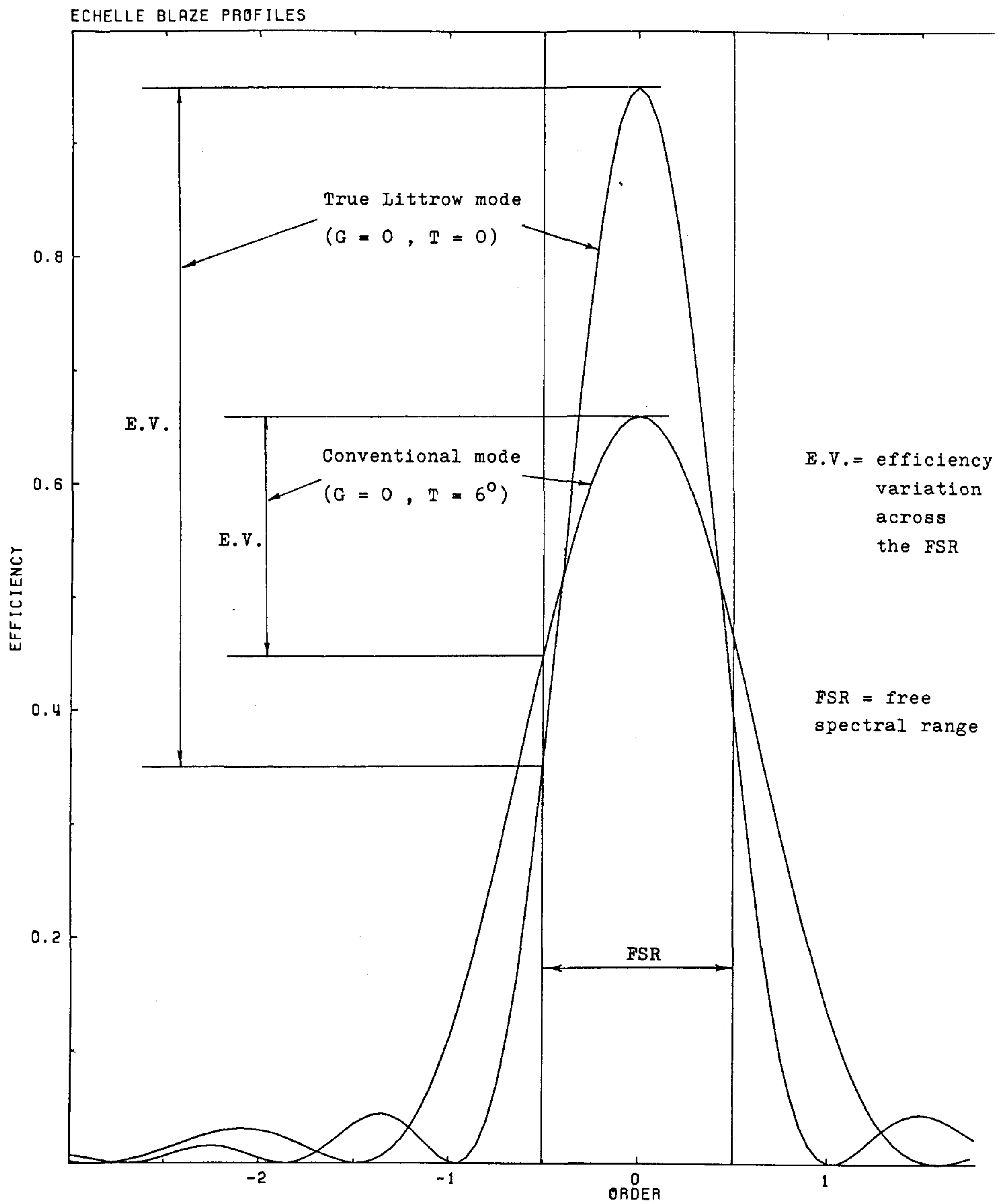

ECHELLE BLAZE PROFILES
True Littrow mode
(G = 0 , T = 0)
E.V.
Conventional mode
(G = 0 , T = 6°)
E.V.
E.V.= efficiency variation across the FSR
FSR = free spectral range
FSR
EFFICIENCY
0.8
0.6
0.4
0.2
-2
-1
0
1
ORDER

Figure 2

the exposure required. Also, in some studies (e.g. statistics of quasar absorption lines), the SNR of the spectrum should be artificially uniformly degraded to the worst value.

The uniformity of SNR is also very important when using a photon counting detector where coincidence losses limit the peak count rate. Thus the sharply peaked Littrow blaze profile effectively reduces the overall dynamic range of the system.

It should be noted that for the same slit width and for a given slit-limited resolution, the beam size is a function of the échelle configuration, so for the same performance, the In-Plane mode will require a smaller beam, which eases the problem of providing a cross disperser of adequate aperture (see Section 6).

Following these arguments, the spectrograph will have the In-Plane configuration. A beam separation of 12° is a good compromise between blaze profile, the size of the diffracted beam (i.e. camera apertures) and the general layout.

6. CROSS DISPERSER

In choosing the cross disperser, the ideal characteristics must be considered:

- Adequate order separation for point sources
- Constant order separation (independent of wavelength)
- High and uniform throughput
- Ability to scan orders across the detector
- Ability to change cross dispersion if required

The dispersive elements available for this purpose are gratings, prisms or grisms. All of them present advantages and disadvantages.

The range of acceptable order separations is narrow. If the orders are too close, then the slit length has to be reduced and there would be problems in deconvolving overlapping spectra. Conversely, if the orders are too widely spaced, the valuable area of the detector is being wasted and more exposures will be required to cover the whole spectral range. It also follows that the order separation should be as constant as possible.

The requirements are best met by a system based on UV transmitting fused silica prisms.

Reflection light losses and excessive polarization limit to $\sim 60^{\circ}$ the apex angle of the prisms. Unfortunately, a single pass 60° prism gives insufficient dispersion and as a result we also considered the double pass

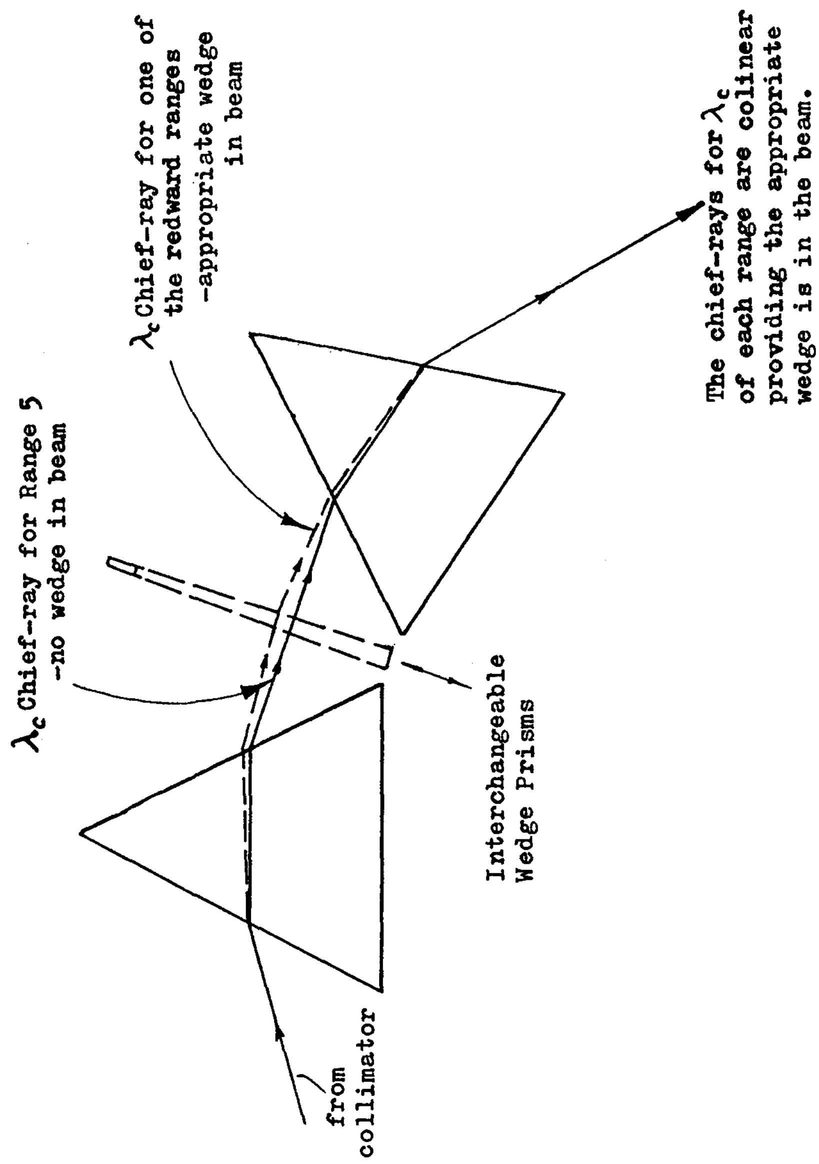


Figure 3

Prism cross disperser

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solution. However, the prisms required are very large by spectrograph standards (sides of about 250mm even for single pass). According to the prism manufacturers we have consulted, it is impossible to obtain fused silica boules of the needed size and internal homogeneity to meet directly a realistic wavefront-error specification of 1/5 wave (3800Å). The solution is to figure the refracting surfaces to correct the wavefront leaving the prism. This works fine for single-pass prisms providing that the refractive-index gradients are not too steep. However, with double-pass, the beam traverses a different part of the prism bulk at the second pass than at the first and this makes local figuring much less effective. (Of course to a marginal extent the problem also arises with single-pass since rays of different wavelengths deviate slightly within the prism due to its dispersion. This is why sharp index gradients can not be tolerated).

We are studying the feasibility of composite prisms, in which two 30° apex angle prisms are glued or oiled together; thus the use of smaller boules would increase the general homogeneity.

The solution we finally adopted comprises two single pass 60° fused silica prisms (each of which could be a composite) in tandem. Scanning across the orders is obtained by the provision of interchangeable wedges which can be interposed between the prisms (figure 3). The system is symmetric, so the prisms work at minimum deviation for the centre of every one of the nine ranges (five principal and four intermediate) into which the total échellogram becomes divided (figure 4). Fine tuning will be possible by tilting the échelle grating in the plane of cross dispersion.

A method of increasing the cross dispersion based on the interposition of transmission gratings is also being studied.

Due to practical limit on prism sizes, the cross disperser must be placed before the échelle since afterwards, the beam is both dispersed and anamorphically dilated.

7. BEAM DIAMETER

In most high-resolution astronomical spectrographs, much of the light from a stellar image is lost at the jaws of a narrow entrance slit. Even with the higher angular dispersion of an échelle, the slit is still normally narrower than the typical seeing disk. The situation can be improved by increasing the beam diameter so that the monochromatic collimated beam overfills the aperture stop (normally the longer dimension of the primary disperser). The longer collimator focal length implies a wider slit, and the gain in light transmitted can more than compensate for that vignetted at the stop. Moreover, for an

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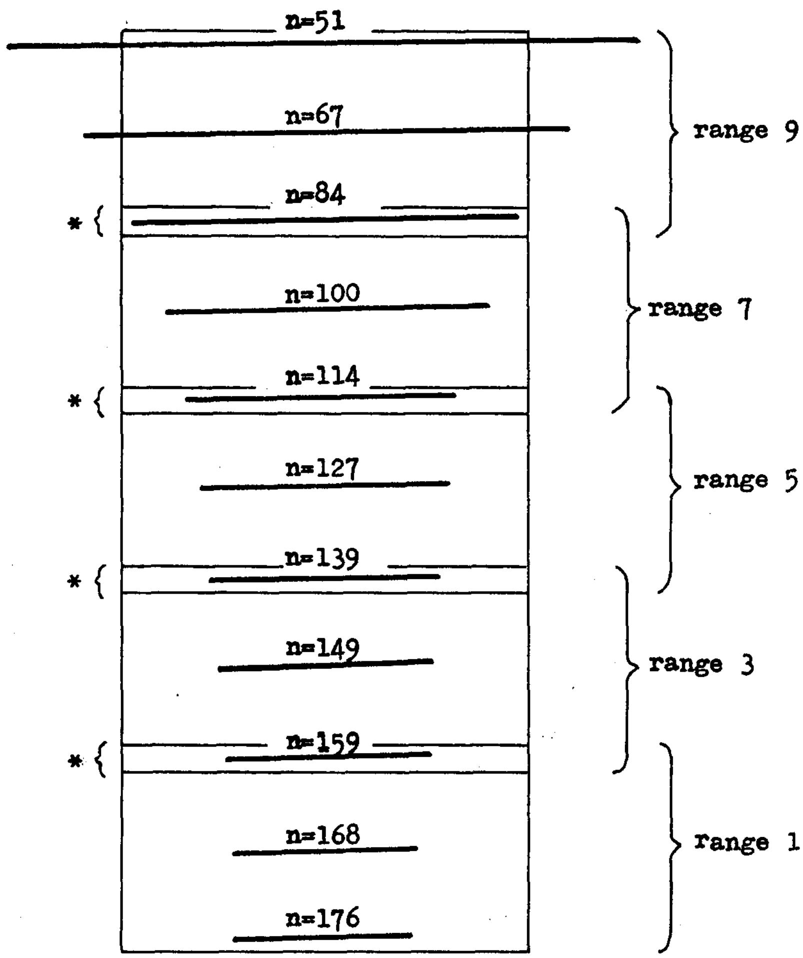
Figure 4. Overlap of the five principal ranges
(as selected by the wedges)



Scale of figure	:	Twice full
Format size for each range	:	30 x 16 mm
Overlap between ranges	:	13% (marked * in figure)

The echelle orders shown are those at the centres of each principal range, and those common to adjacent principal ranges.

There will also be four intermediate ranges (2,4,6 and 8) which are omitted from the drawing for clarity.

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échelle system with restricted order-separations, it enables the necessarily short slit to be lengthened without overlapping of the orders. This can give a further improvement in throughput. The overall gain, compared to a system in which the disperser is just filled, can in principle exceed 30%, depending on the exact configuration and seeing (Diego and Walker, in preparation). Typical results are shown in figure 5.

However, for the AAT coudé-échelle spectrograph, the feasibility of large cross disperser prisms sets the upper practical limit on beam size, so this gain can be only partially realized. A 143mm beam would just fill the échelle's length. The beam in practice will be enlarged to 160mm which is within the range of feasible prism sizes. The net throughput gain for the $\lambda/\Delta\lambda$ = 80,000 mode is then about 12% for a 1.5 arc sec FWHM seeing disk, and 19% for an extended source (figure 5). For the other modes, comparable gains would be expected.

8. OPTICAL LAYOUT AND ANCILLARY FACILITIES

The general layout is shown in figure 6. The f/36 diverging beam from the entrance slit is collimated by an off-axis paraboloidal collimator mirror (there will be two interchangeable collimators with overcoatings for red and blue wavelengths). The collimated beam is dispersed horizontally by the prism system and then in the vertical plane by the échelle grating. The spectrum is imaged onto the detector by the optical camera.

For the short and long cameras, the folded Schmidt type was chosen due to the potential for excellent image quality over a wide spectral range and (flattened) field. Also, the focal plane is externally accessible to a large detector. The central obstruction due to the access hole on the flat mirror is smaller than the obstruction caused by a secondary mirror of an equivalent Maksutov type camera. Future longer cameras (2000mm) would probably have a classical cassegrain configuration with a field flattener lens.

The short camera has the extremely fast focal ratio of about f/1. Moreoever, this mode achieves a wide simultaneous wavelength coverage amounting to half the total échellogram. Unfortunately, these factors make it impossible to avoid an achromatic Schmidt plate with thin glass components. This will degrade the UV transmission close to the atmospheric cut-off. However, this high-throughput, low-resolution mode can be simulated with the long camera which is UV transmitting, by opening the slit and pre- or post- binning the IPCS data. The penalties are: increased dark-signal per pixel and loss of the extensive simultaneous wavelength coverage.

The Plate shows a scale model of the spectrograph in the AAT coudé room.

In the slit area the following facilities will be provided:

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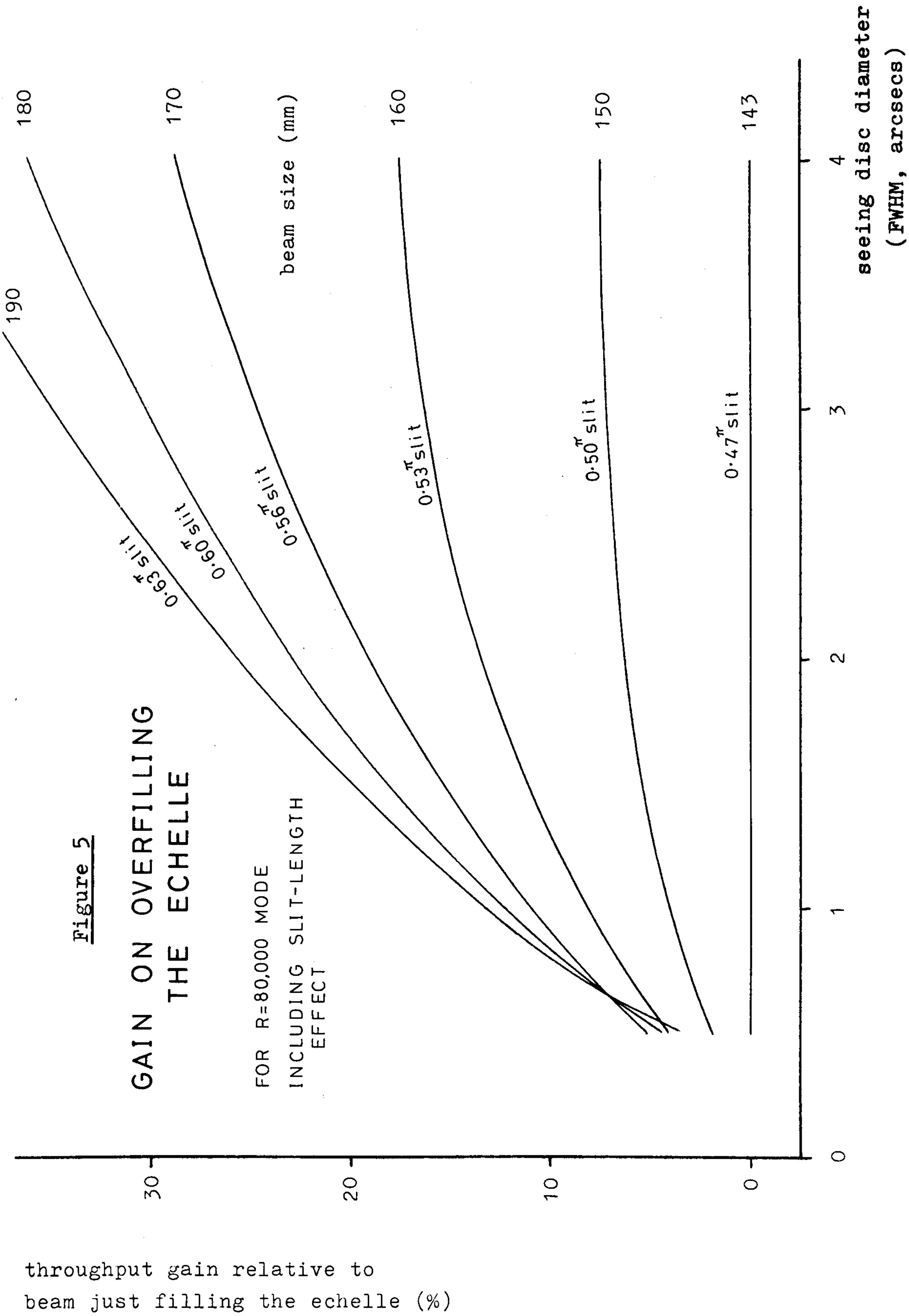

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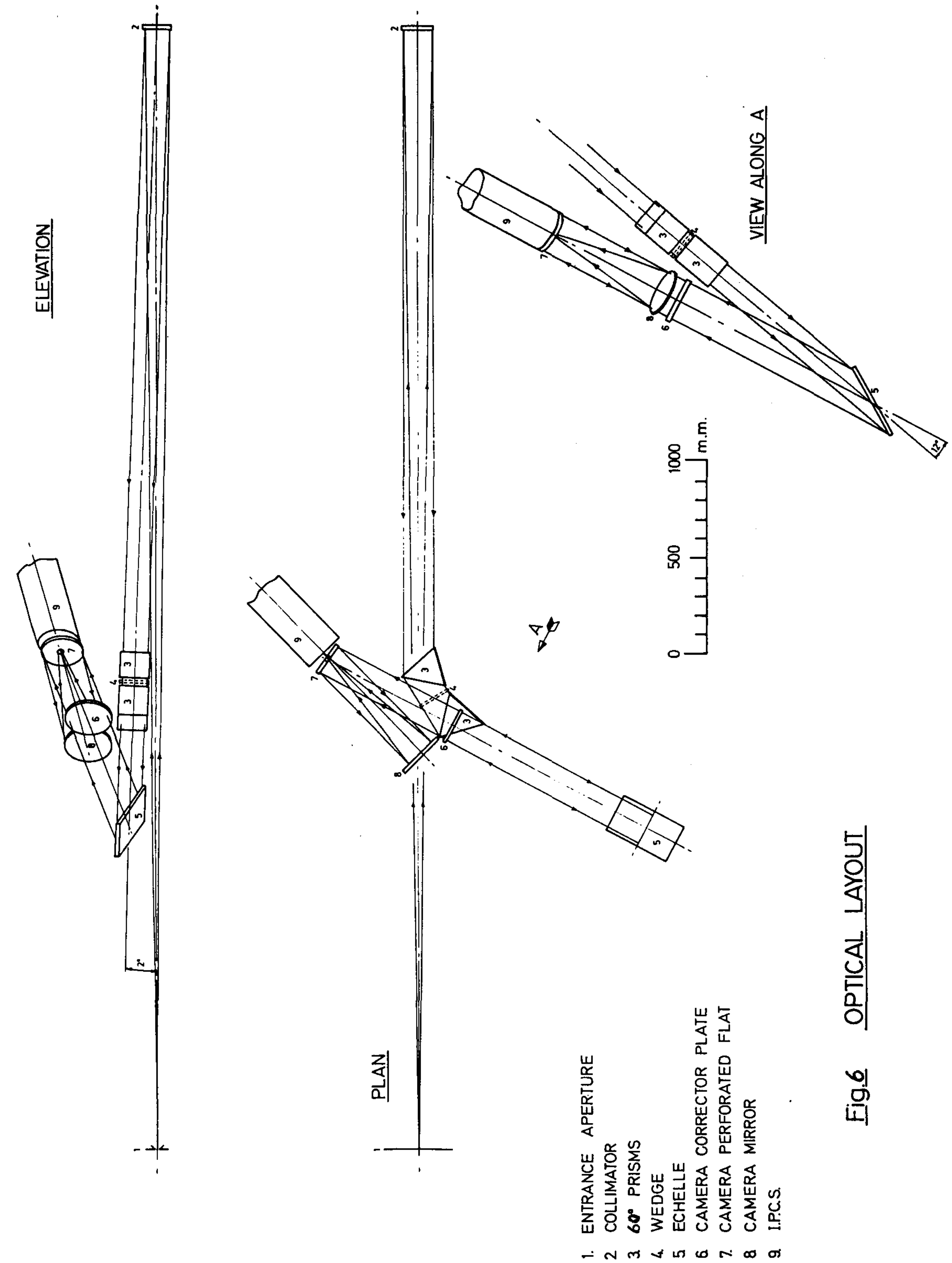

Fig.6 OPTICAL LAYOUT

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- Bi-lateral adjustable and rotatable slit
- Dekker mask
- Interchangeable field-lens/colour filter combinations with optimized anti-reflection coatings.
- Atmospheric dispersion corrector prisms
- Beam rotator prisms
- Periscope prisms for widely-separated pairs of apertures
- Optics for slit viewing
- Comparison-spectrum sources with relay optics for all orders. The sources will emulate the telescope beam.
- Continuum flat field source (this may be transferred to the camera area to illuminate the detector directly).
- Image slicer

Other facilities are:

- Hartmann shutters
- Beam collimation verification system
- Slit shutter
- Light tight detector shutter

All the above facilities, except for interchanging the échelles and cameras and verifying the beam collimation, will be remotely controlled from the AAT instrumentation computer via CAMAC.

9. CONCLUSION AND IMPLICATIONS ON A VERY LARGE TELESCOPE

The combination of the In-Plane échelle configuration with a prism cross disperser provides a very efficient and versatile system well matched to the characteristics of the detector in terms of format geometry and uniformity of intensity.

The expected stellar limiting magnitudes in the V band, calculated for a signal to noise ratio of 10:1 and an integration time of 6 hours, are 15 for the high resolution mode and 17.2 for the enhanced throughput mode.

A spectrograph for a Very Large Telescope (VLT) of about 15m diameter, designed with the aim of retaining the same throughput and resolution under similar seeing conditions would require a beam diameter four times larger. However, considering that the VLT will be implemented at a site with better seeing conditions than the AAT, it is probable that a beam diameter twice as large would be adequate.

In this case, the order separations as projected on the sky would be reduced, but measured in terms of seeing disc diameters, would remain unchanged.

Larger fused silica prisms could be fabricated as composites of several wedges and the échelle could be a mosaic of four 204mm x 408mm standard rulings.

The problem will arise with the cameras, which would have to be twice as fast (larger aperture for the the same focal length) and the long camera would then require an achromatic corrector lens (as does the short camera for the AAT instrument). Hence, the UV coverage of the instrument down to the atmospheric limit would be lost. Furthermore, the short camera would certainly be impossible fast.

The implication is that the cameras' focal ratios should remain the same as in the AAT spectrograph, so the focal lengths would need to be doubled. This will require detectors of four times the area of the present IPCS with at least the same amount of pixels. We are optimistic that such detectors (or the technology for implementing a mosaic of detectors) will become available during the next decade.

Scaling up the AAT system for a VLT, the expected limiting magnitudes would be 18 ($\lambda/\Delta\lambda$ = 80,000) and 20.2 ($\lambda/\Delta\lambda$ = 32,000).

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REFERENCES

Boksenberg, A: 1972, ESO/CERN Conference on Auxiliary Instrumentation for Large Telescopes, p.295, Geneva.

Schroeder, D.J. and Hilliard, R.L. : 1980, A.O. 19, p.2833.