Chapter 2

Instrument Design

The design presented here is for a cross-dispersed echelle spectrograph incorporating the use of an optical fibre input and a CCD detector. As mentioned in the introduction the spectrograph type is dictated by the requirements of compactness and efficiency for use with small to medium aperture telescopes.

The first thing to consider is the overall instrument configuration. Such choices as the mode of grating operation and cross-disperser type must be made.

2.1 Operating Mode

The equation that describes the behaviour of an echelle grating is:

$$m\lambda = d\left[\sin(\theta_b + \theta_i) + \sin(\theta_b - \theta_i)\right]\cos\gamma \tag{2.1}$$

where m is the order number and λ is the wavelength. The meanings of the other parameters are illustrated in Figure 2.1.

The Littrow mode where is the ideal configuration, however in a practical design the input and output beams must be separated. There are two alternatives:

1. Quasi-Littrow mode with $\theta_i = 0, \gamma > 0$, and
2. “in-line" mode with $\gamma = 0, \theta_i > 0$.

A number of factors are effected by the choice of mode.

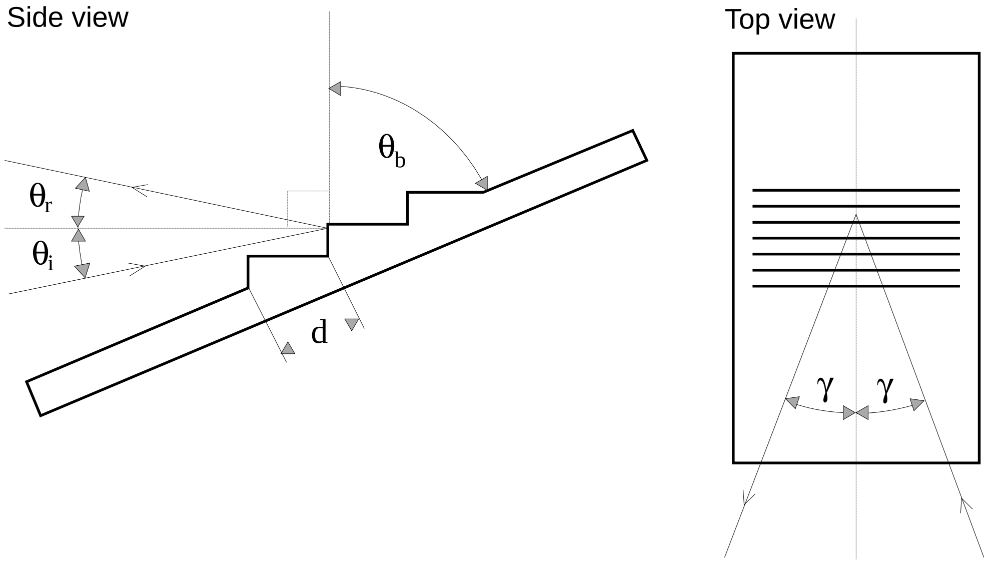

Figure 2.1: Echelle grating parameters.

2.1.1 Through-put

Based on equations developed by Schroeder and Hilliard [1980], the echelle efficiency can be calculated for both operating modes for a single order. The results are plotted in Figure 2.2. Losses due to surface reflectivity of the aluminium coatings are not included. The large blaze angle of echelle gratings results in a non-linear relationship between the angle of the diffracted light and the order number causing a slight asymmetry in the efficiency curves. These calculations are discussed in greater detail in Chapter 5.

Although the “in-line" mode has the advantage of a relatively even response over the free spectral range, FSR, over half of the light is outside the free spectral range. Where more than one FSR falls on the detector, the data from the “tail" of one order may be added to that from the central peak. This method is used by the UES / AAT echelle spectrograph [Walker and Diego, 1985]. However if the system is to be optimised for resolution, then at longer wavelengths, the detector width will typically correspond to a single FSR making the “recovery" only practical for the short wavelength end of the spectrum.

On the other hand the quasi-Littrow mode gives significantly higher

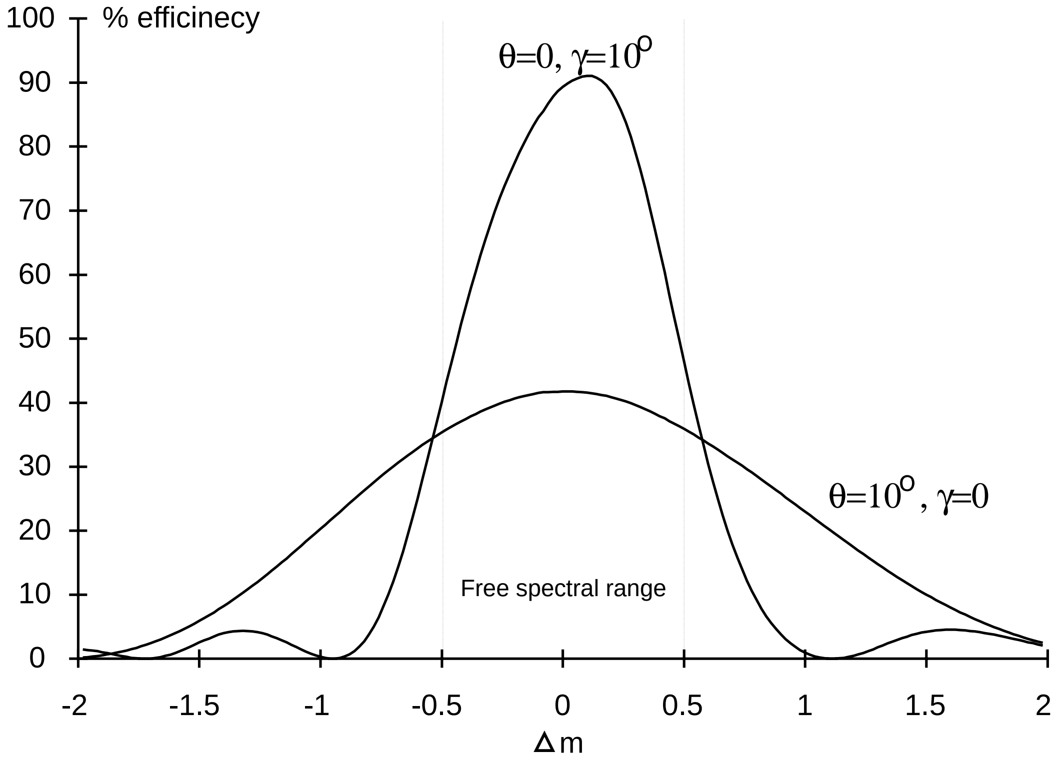

Figure 2.2: Calculated efficiency for a 52g / mm echelle, $\theta_b = 65^\circ$, $m = 60$.

through-put, especially near the blaze peak. Because the spectrograph is a fixed format (no moving parts) design, the large variation in through-put over the free spectral range is well defined and can be easily compensated for during the data reduction process. From the point of view of efficiency, and hence exposure times, a quasi-Littrow mode offers the best performance.

2.1.2 Resolution

Resolution is also effected by the choice of operating mode. As the angle γ is increased to separate the incident and diffracted beams, the image of the input fibre becomes elongated in the dispersion direction resulting in a reduction of the spectrographs resolving power. This is illustrated in Figure 2.3 with full details given in Chapters 4 to 7.

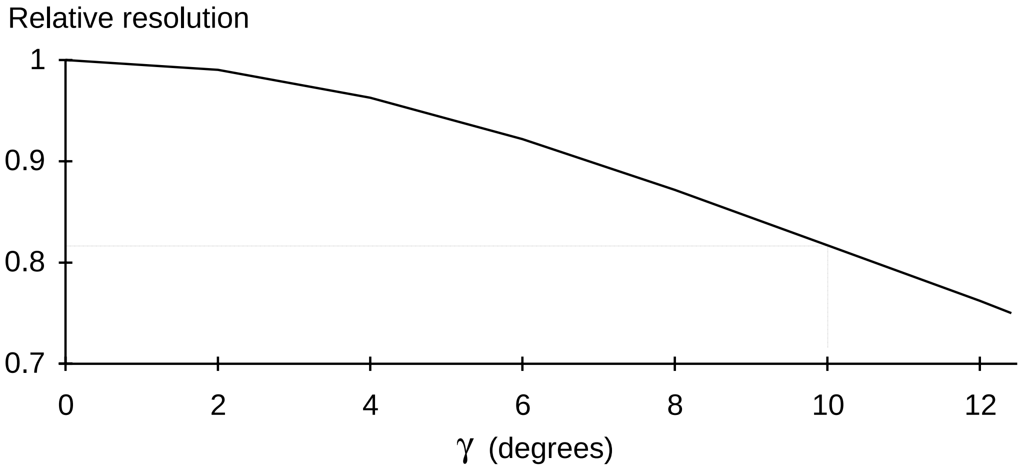

Figure 2.3: Effect of gamma angle on resolution.

2.1.3 Diffracted beam size

In all but a purely Littrow mode the size of the beam diffracted from the echelle is larger than the incident beam requiring a larger, faster camera lens if vignetting is to be avoided. For a quasi-Littrow mode the amount of enlargement can be determined from the transfer matrix of the echelle (Chapter 5). Referring back to Figure 2.1, the enlargement of the beam in the in-line mode can be shown to be $\cos(\theta_b - \theta)/\cos(\theta_b + \theta)$. Both modes are compared in Figure 2.4 for circular incident beams clearly showing disadvantages to the in-line mode for all but the smallest angles of separation.

Apart from a small reduction in resolving power the quasi-Littrow mode of operation offers significant advantages. In addition to this all the optical component will lie in the same plane, simplifying construction (and therefore reducing costs). The physical dimensions of the optical components and the desire for a compact instrument result in a quasi-Littrow mode with a value of $\gamma = 10^\circ$ being chosen. This provides adequate beam separation without excessive loss of resolution.

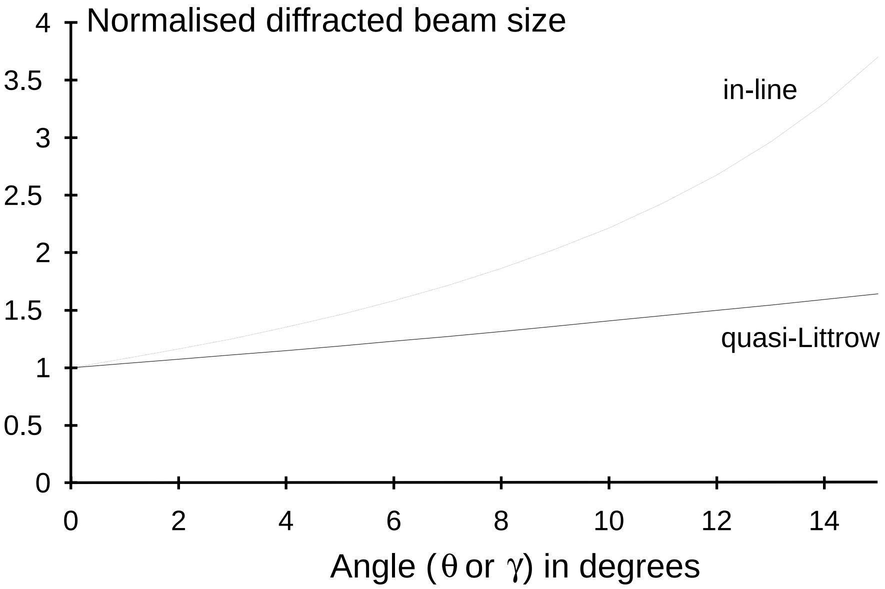

Figure 2.4: The effect of angle on diffracted beam size.

2.2 Cross-disperser Type

The cross-disperser separates the echelle orders giving a 2-D spectrum format. Ideally the separation between orders should be constant, however in practice the separations will vary. Either a prism or grating cross-disperser may be used.

At the central wavelength, λ_m , (when $\theta_i = \theta_r = 0$) for order, m, equation 2.1 can be reduced to show that $m \propto 1/\lambda_m$, therefore, for a constant separation between orders, the cross-dispersion must vary as $1/\lambda$.

If the cross-disperser is a grating used in a single order of interference then equation 2.1 (which is in fact applicable to any grating) can be used to determine its characteristics. It is not difficult to show that the cross-dispersion will vary as λ , which unfortunately is significantly different from what is required. The angular dispersion of a prism, on the other hand, increases from red to blue wavelengths, i.e. as λ decreases. Figure 2.5 illustrates the characteristics of both types of cross-dispersers.

Because it produces a more uniform spacing of the orders a prismatic cross-disperser is more suitable to our needs. There is also the benefit of high efficiency ($> 90\%$ for a coated prism).

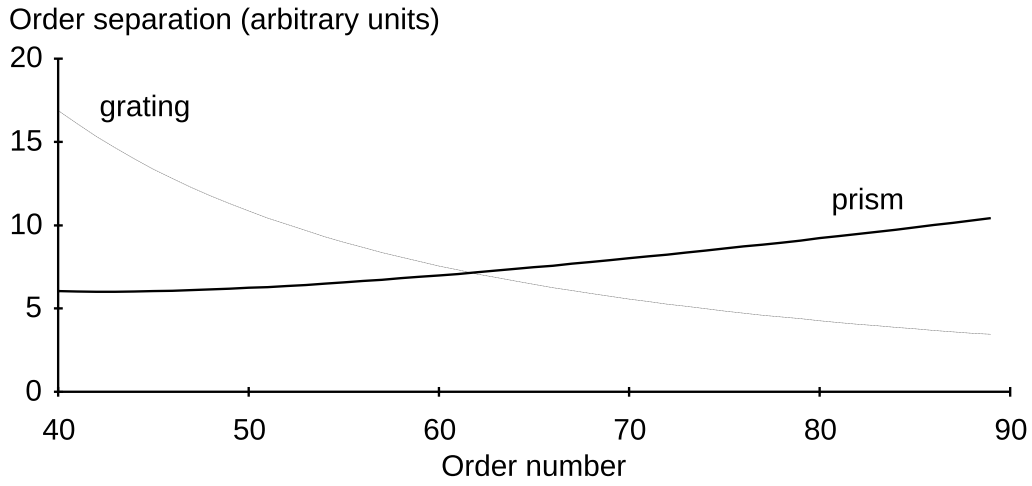

Figure 2.5: Order separation for grating and prism cross-dispersers for the same total dispersion between 400-800nm.

One last decision is whether to put the cross-dispersing prism before or after the echelle grating. The advantages and disadvantages of both positions are discussed in detail by Walker and Diego [1985] with the result that a pre-dispersing prism is considered to be the best solution.

The lay-out of the prototype instrument is shown in Figure 2.6.

2.3 Choice of Optical Components

The major aim when calculating the optical properties of each of the spectrograph's components is to match the geometry of the 2-D spectrum (echellogram) with that of the CCD detector. This must be done in such a way as to obtain maximum through-put at the required resolution of 0.5Å. An additional budgetary restriction excluded the use of custom made optics (which are prohibitively expensive).

The component choices can be conveniently made by using a spread-sheet program to simulate an echellogram. The following factors form the basis of the calculations:

1. The prototype spectrograph is designed to be used on telescopes of up to 1m aperture with focal ratios near f10. This corresponds to a

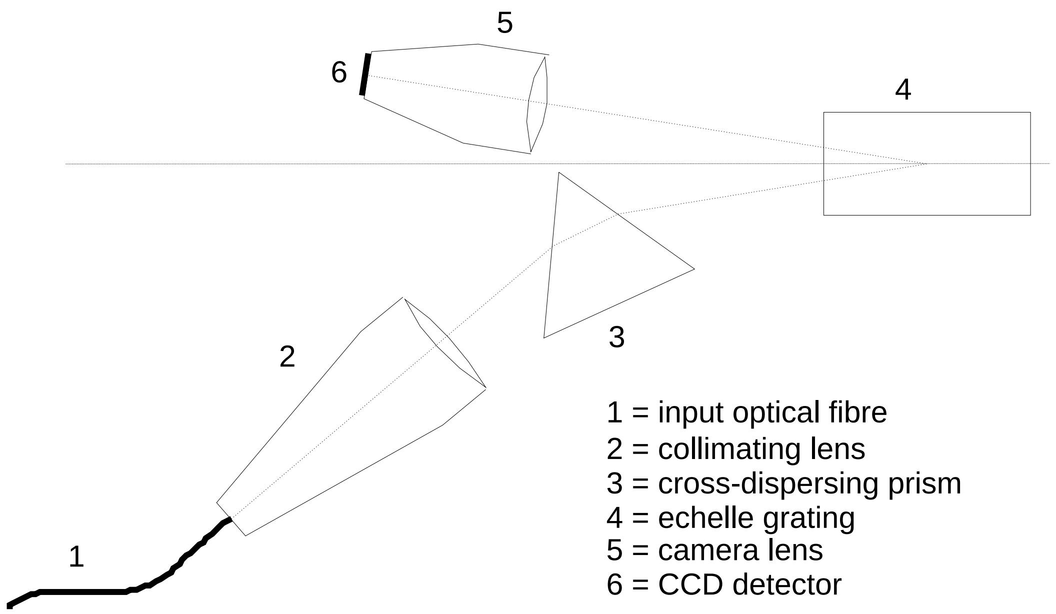

Figure 2.6: Configuration of the prototype spectrograph (not to scale!)

focal length of up to 10 meters. With typical seeing conditions giving 1 to 2 arcsecond resolution a stellar image of approximately 50 to 100μm diameter can be expected. For smaller telescopes the image size will be somewhat smaller.

2. The collimator f-ratio should be less than that of the telescope to minimise light loss due to focal ratio degradation in the fibre. The aperture of the collimator must match the width of the grating. With these limits in mind, a commercial camera objective will be used as a collimator during evaluation of the prototype.

3. Grating parameters are chosen so that when the widest order fills the width of the detector CCD (800-1000 pixels wide) a resolution of at least 0.5Åis possible. To allow reasonable separation the spectrum (visible) should be covered in approximately 50 orders.

4. Ideally the cross-disperser will cause the 50 (approx) orders to just fill the detector while maintaining an adequate minimum order separation.

5. The camera/detector system must be matched with the other components so that the echellogram nearly fills the detector area. The

camera lens focal length will determine the size of the echellogram as well as, in conjunction with the collimator, the size of the fibre image and hence the resolution. The aperture of the camera lens must be sufficiently large to avoid vignetting of the dispersed beam. The number of pixels in the detector needs to be large enough to allow the desired resolution to be achieved (i.e. at least 2 pixels per resolution element) as well as allowing at least one dark pixel (preferably more) between adjacent orders. A blue response at least down to 400nm is required.

With the above restrictions and factors in mind the component parameters are as follows:

Fibre:	High OH silica fibre with 100μm core diameter: Polymicro FHS 100/140/500, 4 meters long.
Collimator:	Kimunor 400mm f6.3 camera objective.
Prism:	BK7, apex angle 60°, incident angle 49° (minimum deviation). ** to be replaced by 3 UBK7 prisms at a later date.
Echelle:	Milton Roy 52.67 groves/mm, blaze = 65°, 56 × 128mm ruled area.
Camera:	Cannon 135mm f2.0 camera objective.
Detector:	Texas Instruments TC215 CCD, 1000H × 1018V 12μm square pixels. 500H × 509V 24μm square pixels with 2 × 2 binning. ** not available for testing of the prototype.

Using these parameters, the layout of the echellogram can be calculated and compared to the detector size. This is shown in Figure 2.7.

Although the format of the echellogram is clearly not optimal it is sufficient to allow analysis and testing of the prototype design. As already indicated the final cross disperser will consist of three prisms chosen to make full use of the detector area. Note also that the initial testing of the prototype, as described later in Chapter 8, utilises a standard 35mm SLR film camera and a small format CCD because of unavoidable development delays for the TC215 based CCD camera.

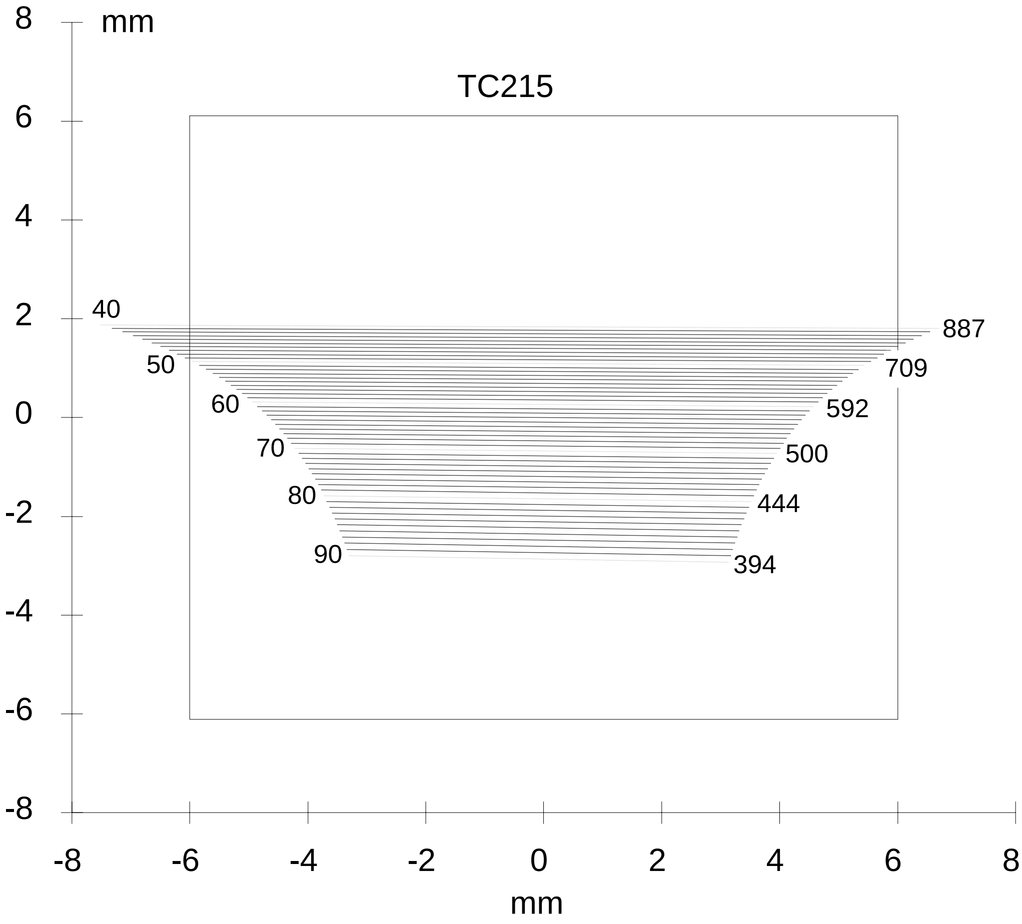

Figure 2.7: The output format of the prototype spectrograph with a single BK7 prism. Order numbers are shown to the left and central wavelengths (nm) to the right.