Chapter 3

Updating the Spectrograph

This project began by upgrading the previous spectrograph design. This is discussed in this chapter.

During testing of the prototype spectrograph (see Section 2.3), it was observed that the image of the echellogram was well defined over only a limited range of wavelengths. This was particularly evident while taking the solar spectra measurements. After further investigations it was found that this was almost completely due to chromatic aberrations in the commercial camera objectives used for the camera lens, and to a much lesser extent, the collimator.

The other aspect of the spectrograph which need addressing was the choice of a suitable CCD camera / detector system. A brief review of the choices made are given later in this chapter.

3.1 Upgraded Collimator Design

Chromatic aberrations not withstanding, initial testing indicated that the chosen commercial camera objective was adequate for use as the collimator. Concerns about the performance of this lens in the near-visible regions of the spectrum, however, has led to the upgrading of the collimator to use reflective optics. Readily available components, higher throughput and a complete absence of chromatic aberrations, are all factors which make the use of reflective optics preferable.

The collimator is constructed as a single unit consisting of a 400mm focal length parabolic mirror in an adjustable mount. A focal ratio of f8, and hence the beam size, is set with a 50mm diameter aperture mask. The end of the optical fiber is supported by a thin metal vane at the mirror's prime focus. The new collimator is illustrated in Figure 3.1.

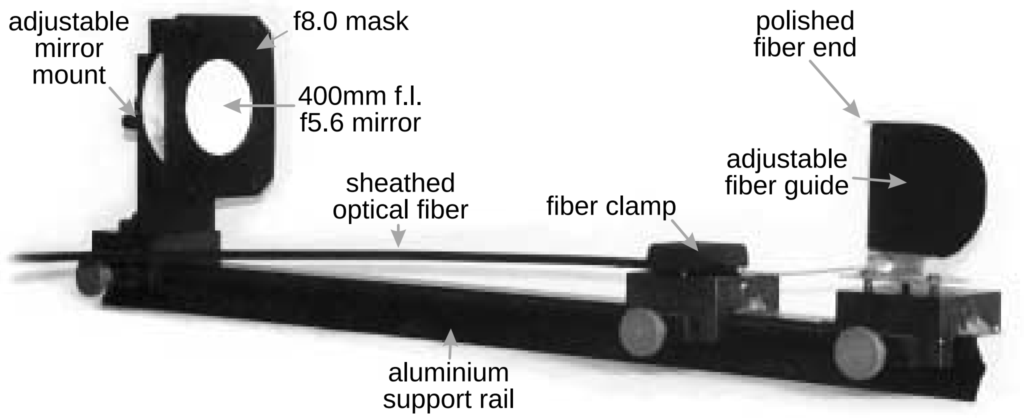


Figure 3.1: Upgraded collimator using reflective optics.

3.2 Camera Lens Aberrations

Measurements by Baudrand and Böhm [1992] of the chromatic aberration of various 400mm f2.8 camera objectives were used as a guide during the initial design of the spectrograph [Porter, 1993]. Peak to peak deviation of the focal plane was quoted as less than 0.03% over the range of visible wavelengths. In contrast to this, a simple achromatic doublet has chromatic aberrations an order of magnitude larger.

The Canon 135mm f2.0 camera objective chosen for use in this spectrograph, with it's shorter focal length and faster optics, was assumed to have larger errors than the lenses tested by Baudrand and Böhm, however initial testing of the spectrograph indicated that the overall magnitude of the errors was significantly greater than initially expected. Subsequent measurements have proved this to be the case.

3.2.1 Test Results

Testing of the camera objective was carried out by measuring the focal length for a range of wavelengths. A simple monochrometer was used to provide variable wavelength illumination for a target placed at a fixed distance from the lens. By adjusting the position (with respect to the lens) of a small CCD camera, the optimum focal plane position over a

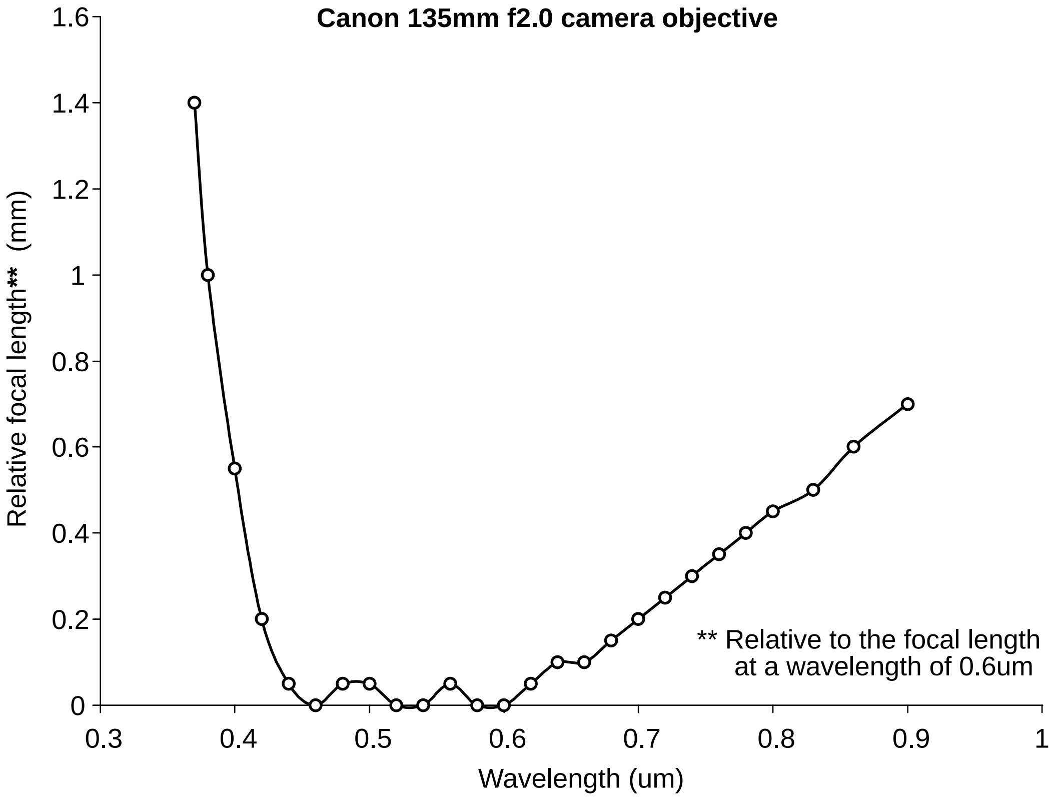


Figure 3.2: Canon 135mm f2.0 camera objective test results.

range of wavelengths was determined. To minimise systematic errors the measurements were repeated for a number of target-lens distances. Finally, for the purpose of calculations, the manufacturers stated focal length for the lens was assumed to be specified at a wavelength of 600nm. A summary of the test results are plotted in Figure 3.2.

It is illustrative to refer back to the results from Baudrand and Böhm. Their results would indicate that the differences in performance between the lenses from different manufacturers is primarily in the shape of the curve rather than in the magnitude of the errors. A similar situation would probably exist for the 135mm f2.0 lenses such as that being measured here.

3.2.2 Implications for a Single Exposure Design

In order to put the test results into perspective, it is necessary to calculate the effect of the errors on the spectrograph resolution. From Porter [1993], the resolving power of the spectrograph is given by:

$$\frac{\lambda}{\delta\lambda} = \frac{2F_k \tan\theta_b}{D} \tag{3.1}$$

where F_k is the camera lens focal length and θ_b the blaze angle of the echelle grating. D is the minimum separation between the images formed by two wavelengths that allows those images, and hence the corresponding spectral features, to be resolved. Usually D is determined from the integrated profile, in the dispersion direction, of the fiber image.

In practice an estimate can be made from the value of D for an ideal image of the fiber, D_{fiber}, and the diameter of the image of a point source due to focusing errors in the camera lens, D_ε. Using the results from the author's original theoretical resolving power calculations [Porter, 1993], the following equation was empirically derived:

$$D \approx \sqrt[3]{D^3_{fiber} + (0.9D_\varepsilon)^3} \tag{3.2}$$

The echellogram (Figure 2.2) together with the wavelength-dependent focal position (Figure 3.2) are all that is needed to determine the actual focal surface of the spectrograph. The resolving power of the spectrograph can now be found at any wavelength with the aid of equations 3.1 and 3.2, and from the difference between the actual focal surface and the plane of the detector. Fortunately things can be simplified further.

Because each of the spectral orders covers only a very limited range of wavelengths, it is therefore sufficient to consider only the variation of wavelength in the cross-dispersion direction. Figure 3.3 shows a plot of the relative focal length versus cross-dispersion and, with the aid of equations 3.1 and 3.2, the range of positions at which a given resolution can be achieved. Also shown on this plot is one of many possible detector positions illustrating the limited range of wavelengths, in this case 415nm to 660nm, over which the design wavelength resolution of 0.5Å is achievable in a single exposure.

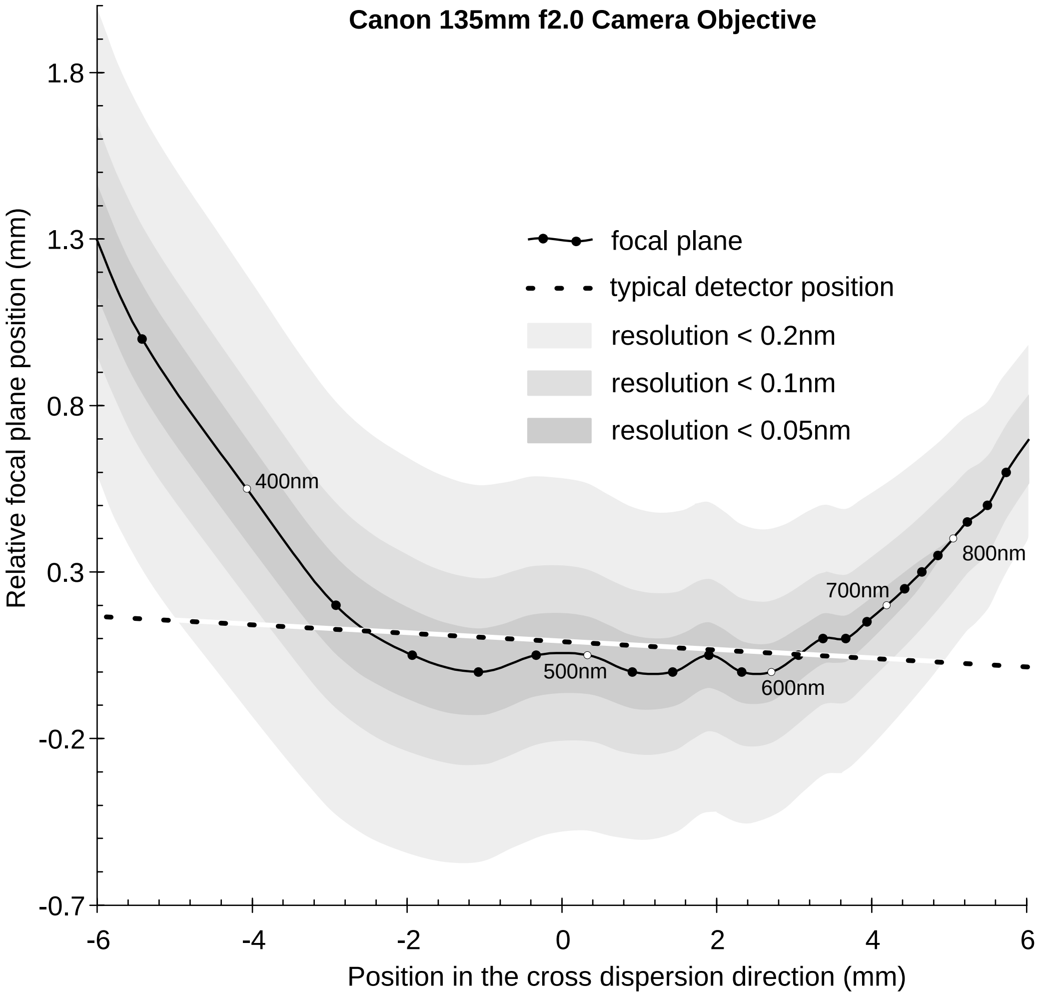


Figure 3.3: Image position in the cross-dispersion direction.

3.2.3 Multiple Exposure Designs

One method of achieving optimum performance over a wide range wavelengths is to use multiple exposures with each having only a limited part of the overall spectral coverage.

Sequential Exposures

The most obvious method of performing multiple exposures is analogous to that of a traditional spectrograph. In the traditional design, the position of the dispersive elements are adjusted to bring a desired range of wavelengths into focus on the detector. In contrast to this, modification of

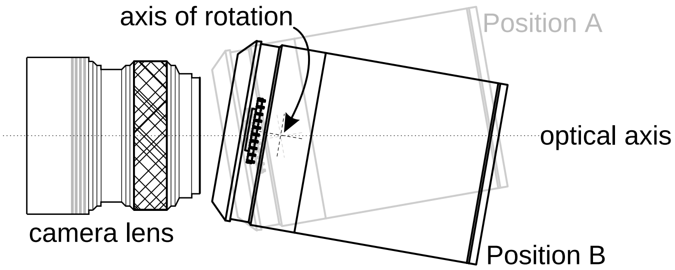


Figure 3.4: A simplified sequential exposure system (detector movement exaggerated).

the basic echelle spectrograph would provide for adjustment of only the detector position.

Referring again to Figure 3.3, it can be seen that the focal surface can be approximated, at least within allowable tolerances, by a cylinder. The radius of this cylinder is about 18mm. This implies that positional change for the detector consists of simply rotating the detector about an axis orthogonal to the optical axis and the cross-dispersion direction. Using this technique complete visible spectral coverage could be obtained in only three exposures. The general principal is illustrated in Figure 3.4.

Because wavelength, and hence the focal length of the camera lens, also changes in the dispersion direction, the optimum orientation for the axis of rotation will be slightly different from that mentioned. Fine adjustment of the camera lens focus may also be required to optimise performance at each exposure position.

An advantage of a sequential exposure systems is that a CCD detector of smaller area (but at least the same size in the dispersion direction) may be used. Alternatively the amount of cross-dispersion could be increased to allow the use of multiple fibers so that two or more objects could be measured simultaneously.

The obvious problem with sequential exposure systems is the potential increase in measurement times. In many cases, however, measurements are required on only a limited range of wavelengths and could be achieved in a single exposure.

Tri-chromatic Systems

The solution to the long measurement times of the sequential exposure systems is to make the multiple exposures concurrently. By way of example, consider the manner in which professional colour television cameras operate. Here light exiting the lens is split into three bands (red, green and blue) using a pair of dichroic filters. A separate detector, usually a CCD, is then used for each band.

Similarly for the echelle spectrograph, the light would be split using *dichroic* mirrors into three wavelength bands. With a separate detector for each band, all bands may be detected simultaneously. Unfortunately the fast focal ratios used for the camera mean that, both optically and physically, such a system difficult, if not impossible, to construct. Placing the dichroic filters before the camera lens would solve this problem at the expense of requiring three complete camera/lens systems. Note that there is no requirement for them to be identical.

At this stage it is tempting to just pessimistically write-off the tri-chromatic system as too expensive. Referring back to Figure 2.2, however, it can be seen that each of the CCDs may be much smaller than that required for a single exposure system, especially the “blue” CCD. Furthermore the limited wavelength range for each of the lenses implies the possibility of simpler, less expensive optics.

3.2.4 Custom and Corrective Optics

Although the multiple exposure systems provide a way of circumventing the shortcomings of the commercial camera objective, they do so at the expense of increased measurement times and/or increased instrument complexity and cost. Another approach is to utilise custom optics to either replace or correct the commercial lens.

Custom Optics

The ultimate solution is of course to design a set of custom optics. Although the spectrograph will certainly require some custom made optical components, the cross-dispersing prisms for example, the design and construction of a complete camera objective is, at this stage at least, not considered a financially viable option. It must be pointed out, however, that until all options are considered on a cost/performance basis, the eventual use of a custom camera objective can't be ruled out.

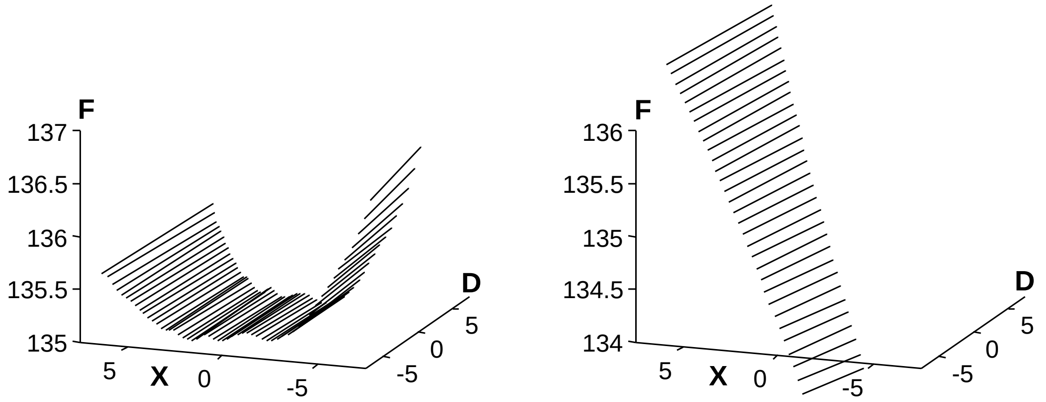
Corrective Optics

Recall that the difficulties lay in the fact that, due to chromatic aberrations, the focal surface is not flat, nor even spherical. Corrective optics would therefore be required to flatten the focal surface *but not necessarily make it normal to the lens' optical axis.* One method would be to provide "field flattening" optics in a similar manner to that used in some telescope designs. Unfortunately this option is not viable because of the cylindrical shape of the focal surface. Such corrective optics would not only be asymmetric, and hence difficult to produce, but may also introduce significant amounts of other aberrations such as coma.

With the previously mentioned requirements in mind, a more direct approach is to correct for the chromatic aberrations. To illustrate the possibilities, standard two dimensional echellograms were plotted against the wavelength-dependant focal lengths for a number of lens combinations. The resultant 3D plots, shown in Figure 3.5, effectively illustrate the shape of the focal surfaces. Considering these focal plane plots:

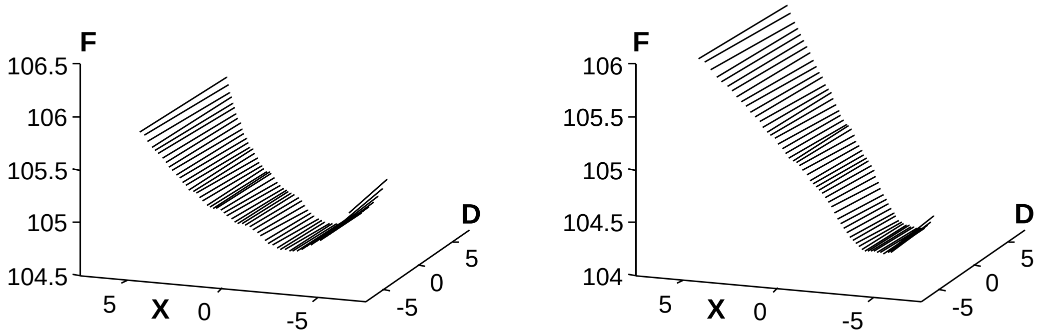
(a) The roughly cylindrical shape of the Canon objectives focal surface is clearly illustrated.

(b) A simple lens made from the same material as the cross-dispersing prisms, BK7, will provide a flat focal surface as required. Unfortunately this is not usable because of the excessive inclination, especially considering the relatively fast focal ratios being used.



(a) Canon 135mm f2.0

(b) BK7 135mm



(c) Canon 135mm + BK7 450mm

(d) Canon 135mm + F1 450mm
with 1/2 cross-disp' by grating

Axes: **D** = dispersion (mm), **X** = cross-dispersion (mm), **F** = focal length (mm)

Figure 3.5: Focal plane plots for various lens combinations.

(c) Using a compound system with a BK7 "corrector" lens for the Canon objective produces a notable improvement over the Canon objective alone.

(d) Further improvement is obtained by using a flint glass, F1, for the corrector. The cross disperser has also been modified by replacing one of the prisms with a grating having similar overall dispersion. Note that the inclination of the focal surface is significantly less than that for the simple BK7 lens in (a).

Compound systems, where the chromatic aberration of a simple, single glass lens is used to correct that of commercial camera objective, provide a viable and economic alternative to custom optics. Further improvement may also be possible with the use of more exotic glass for the corrector and / or a commercial camera objective from a different manufacturer.

One final point is that shortening the overall camera focal length is advantageous in this spectrograph design because it results in a better match between the echellogram and the TC215 CCD detector area. Contrary to what may be expected, there would be no loss of resolution because the 12μm pixel size of the detector is sufficiently small to still fully sample the image of the fiber.

3.3 Choosing a Camera

A CCD camera / detector system was also needed for use as part of the spectrograph. A number of factors were considered when determining the source of a suitable camera, including:

- As with the overall spectrograph, cost-effectiveness was deemed important. This was further enforced by a project budget of only modest proportions;
- Because the application involves extremely low light levels, the camera must be capable of long exposure times;
- Utilisation of the TC215 CCD detector already in our possession.

Of the ready-built cameras, those which could be classed as research grade cameras, including systems which would allow use of the TC215 CCD, cost well beyond what available funding would allow. On the other hand, Commercial grade cameras, such as those designed for use by non-professional astronomers, often are limited in their usefulness in spectrographic applications by factors such as limited response to shorter wavelengths, and design limitations which restrict their maximum exposure times.

After giving the matter due consideration, it was decided that on a cost / performance basis, a custom design would best fill our needs (Chapter 6). Difficulties in implementing this design, however, resulted in the original custom design being replaced by a “kit” camera from Southwest Cryostatics (Chapter 8).