SPECTROSCOPY ON SMALL TELESCOPES: THE ECHELLE SPECTROGRAPH

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Abstract. In recent years there has been a trend toward the automation of modest sized observatories, especially those involved with photoelectric photometry. Although undoubtedly useful, there is clearly a need for more advanced instrumentation such as spectrographs. The relatively small telescope sizes places severe limits on the choice of spectrograph configuration. A fiber-fed echelle spectrograph is arguably the most suitable design for these applications.

Presented here is a brief discussion of the design philosophy and operating principles. Both theoretical and measured performance data for the prototype University of Queensland Echelle Spectrograph are also presented.

Modest sized telescopes, that is telescopes of less than 1 metre aperture, are playing a far more important role in astronomy today than ever before. Apart from the obvious applications of visual observing and astrophotography, this class of instrument has become a vital tool for photometric observations, especially when extended observation runs are required. One such example is the study of variable stars using stellar photometry. Occasionally, however, the object being observed may exhibit an 'outburst' or sudden significant increase in light output. If this occurs then supporting spectroscopy can yield important additional information about the nature of the outburst. Unfortunately, in most cases, access to a suitable telescope and spectrograph at only a moments notice is rarely possible. This is just one example of how the inclusion of more advanced instrumentation, such as spectrographs would be a great advantage.

1. Design Philosophy

When considering a spectrograph for use on telescopes of less than 1 metre aperture, there are major implications for the design of the spectrograph. For the spectrograph to be mounted on the telescope it would have to be both small and of low mass. Even the larger telescopes often used in robotic observatories have little space for additional instrument packages. Fortunately this can be solved by mounting the spectrograph away from the telescope and using an optical fiber to transfer the light. Although no longer mandatory, a compact design is still desirable to allow installation in smaller observatories. Transportability, and the possibility of

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an environmentally controlled enclosure being used, are factors that may also be worth considering.

The limited light gathering ability of these modest size telescopes also places restrictions on the design. For the spectrograph to be of practical use then both complete visible spectral coverage and short measurement times are required. This is especially true if the spectrograph is to be part of an automated system. Even a moderate resolving power of $\sim$ 20000 is in conflict with this requirement if a standard design of grating spectrograph is used. Being capable of acquiring only small sections of spectrum at a time, a standard grating spectrograph can only achieve wide spectral coverage by the use of a large number of exposures and hence long overall measurement times result. The solution is to use an echelle spectrograph design.

The general theory of the echelle (French for ladder, scale or pair of steps) and techniques for it's production were first discussed by Harrison, 1949, but it was not until the late 60's that the successful production of high quality replica echelle gratings aroused the interest of astronomers. Much of this interest is due to some important properties of the echelle (Schroeder, 1970):

– An echelle grating has a much higher angular dispersion than a low blaze grating, allowing the use of shorter camera and collimator lenses. This can facilitate the design of a compact instrument;
– Of particular advantage to applications on telescopes of limited light gathering ability, the optical through-put of an echelle spectrograph is larger than a normal grating instrument at the same resolution;
– Each exposure provides large wavelength coverage in a convenient 2-D format for electronic detectors such as CCDs. Complete visible spectral coverage can often be achieved with only one or two exposures.

Although the spectrograph design details are dependant on the particulars of the intended application, an echelle spectrograph design with moderate resolving power of 10000 to 20000 would suit most requirements.

2. The Echelle

An echelle grating is a plane reflection grating with a very large blaze angle, typically about 60°, and a course groove spacing in the order of 10 μm. Unlike the traditional plane grating which is often used in the first order, the echelle grating is used at much higher order numbers. The dispersive behavior of an echelle grating is described by the equation

$$m\lambda = d\,[\sin(\theta_b + \theta_i) + \sin(\theta_b - \theta_r)]\cos\gamma \tag{1}$$

and the angular dispersion is

$$\frac{d\theta_r}{d\lambda} = \frac{m}{d\cos\gamma\cos(\theta_b - \theta_r)} \tag{2}$$

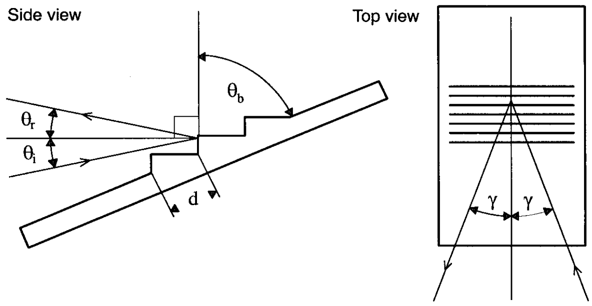

Figure 1. Echelle grating parameters.

where *m* is the order number and λ is the wavelength. The meanings of the other parameters are illustrated in Figure 1.

A brief look at equations 1 and 2 shows that the high angular dispersion of an echelle grating comes from the use of high order numbers rather than fine groove spacing. Furthermore the spectrum is ‘split up’ over a large number of orders with the implication that not only is the angular extent of each order moderately small but that any wavelength will be at or near the blaze peak of one of the orders. These are the primary reasons behind the important properties mentioned at the end of the previous section.

Finally it is necessary to separate the orders using a second low-dispersion grating or prism. This cross-disperser has, as the name implies, a dispersion direction orthogonal to that of the echelle grating. An example of the resulting 2-D spectrum, or echellogram is illustrated in Figure 2.

A detailed look at the theory of the echelle is beyond the scope of this paper. For further information the reader is referred to Harrison (1949) and the papers by Schroeder.

3. Spectrograph Design Example: the UQES

By way of example, a brief overview of the design of the prototype University of Queensland Echelle Spectrograph (UQES) is presented here. This instrument was developed by the author (Porter, 1993) from 1990 to 1993 to provide a spectrograph for use on automated telescopes of less than 1 metre aperture. The goal was to provide complete visible spectral coverage at 0.5 Å resolution. It was hoped to achieve this in a single exposure.

Before continuing with a description of the design, it is important to note that the choice of an individual component can not be made in isolation. The optical properties of each of the spectrograph’s components must be chosen to match the geometry of the echellogram with that of the CCD detector while maximising through-put at the desired resolution. For this reason the use of computer software

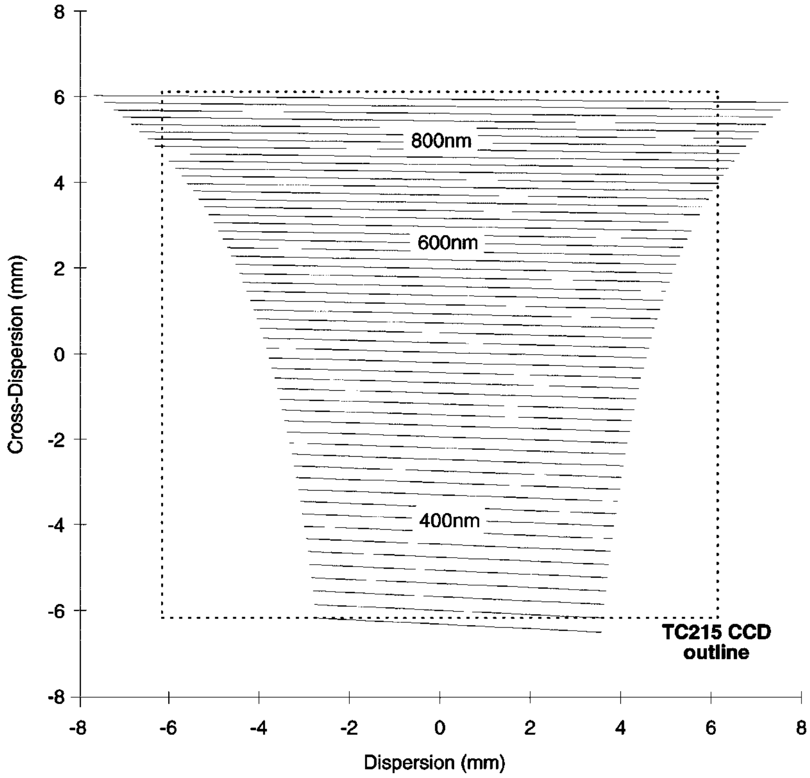

Figure 2. Simulated echellogram for the UQES.

to simulate various parameters of the echelle spectrograph is essential. The author used a standard spreadsheet program for this purpose with the echellogram shown in Figure 2 being the result of one such simulation.

3.1. Spectrograph configuration

Referring back to Equation 1, the ideal configuration is the Littrow mode, where $\theta_I = \gamma = 0$. In a practical design, however, the input and output beams must be separated. The first alternative, the Quasi-Littrow mode of operation, is to make $\gamma > 0$. Characteristics include high through-put near the blaze peak, mechanical simplicity because all the optical component will lie in the same plane, and a slight reduction in resolving power as γ is increased.

There is also an In-line mode where the input and output beams are separated by making $\theta_i > 0$. This mode has the advantage of a relatively even response over the width of each order however the maximum through-put is significantly less than for the quasi-Littrow mode. Given the intended application of the spectrograph then the quasi-Littrow mode with its higher throughput (Schroeder and Hilliard, 1980) and simplified mechanical layout, was considered the most suitable. A value of $\gamma = 10°$ was chosen to provide adequate beam separation without excessive loss of resolution.

3.2. Cross-disperser type

It is desirable to have a constant separation between orders. By setting $\theta_r = \theta_i$ in Equation 1, it is easily shown that, for constant separation, the cross-dispersion should vary as $1/\lambda$. The angular dispersion of a prism increases as λ decreases, producing a reasonably uniform spacing of the echelle orders. On the other hand if a grating cross-disperser is used then the standard optical grating equations give the result that the cross-dispersion will vary as λ. For this reason a prismatic cross-disperser is usually considered more suitable.

It must also be decided whether to put the cross-disperser before or after the echelle grating with the advantages and disadvantages of both positions being discussed in detail by Walker and Deigo (1985). For the UQES a pair of 62°, coated UBK7 pre-dispersing prisms were chosen.

3.3. Choice of optical components

Following is a brief summary of the main design decisions and the resultant component choices.

Fiber: The prototype spectrograph was designed to be used on telescopes of up to 1m aperture with focal ratios near f10. With typical seeing conditions giving 1 to 2 arcsecond resolution a stellar image of approximately 50 to 100 μm diameter was expected. A 4 metre length of 'high OH' step index silica fiber with a 100 μm core diameter was used. The fiber, Polymicro FHS 100/140/500, was generously donated by the Anglo-Australian Observatory.

Collimator: The collimator f-ratio should be less than that of the telescope to minimise light loss due to focal ratio degradation in the fiber. The aperture of the collimator must also match the width of the grating. With these limits in mind, a commercially available 400 mm f6.3 camera objective, used at f8, was chosen as a collimator during evaluation of the prototype.

Echelle grating: Grating parameters were chosen so that when the widest order fills the width of the detector CCD (800–1000 pixels wide) a resolution of at least 0.5 Å is possible. To allow reasonable separation the spectrum (visible) should be covered in approximately 50 orders. The grating used was a Milton Roy with 52.67 groves mm^{-1}, 65° blaze angle and a 56 $\times$ 128 mm ruled area.

Cross-disperser: Ideally the cross-disperser will cause the 50 (approx) orders to just fill the detector while maintaining an adequate minimum order separation. As previously mentioned, a pair of 62° UBK7 prisms were chosen.

TABLE I
UQES performance

Parameter	Value	Conditions
Resolving power	15000	Lines of equal intensity
Maximum efficiency	21% at 650 nm	Includes fiber and CCD
Minimum efficiency	3%	400 nm to 800 nm
Limiting magnitude	11	CCD cooled to –60 °C
Exposure time	100 seconds	56 Eri, Mv = 6

Camera lens and detector: 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 fiber 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 as well as allowing at least one dark pixel between adjacent orders. A Canon 135 mm f2.0 camera objective and Texas Instruments TC215 CCD (1k $\times$ 1k 12 μm square pixels) were found to provide the best combination within budgetary limitations.

Although not ideal, these choices were considered sufficient to allow analysis and testing of the prototype design. Needless to say, the collimator and camera optics are the subject of ongoing development. Overall layout of the spectrograph is shown in Figure 3.

4. UQES Performance and Results

The resolving power and efficiency of the spectrograph was calculated from a combination of the theoretical and measured characteristics of the individual optical components. Estimates of the required exposure times where then made for various astronomical objects. An ‘ideal’ telescope of 1 metre aperture and a focal ratio of f10 or greater was used for the purposes of calculation. A summary of these results is presented in Table I with a segment of the solar spectrum taken with the prototype instrument in Figure 4.

While taking the solar spectra measurements, it was observed that the image of the echellogram was well defined over only a limited range of wavelengths. This is due to much larger than expected chromatic aberrations in the camera lens making this, and presumably similar lenses from other manufacturers, unsuitable if

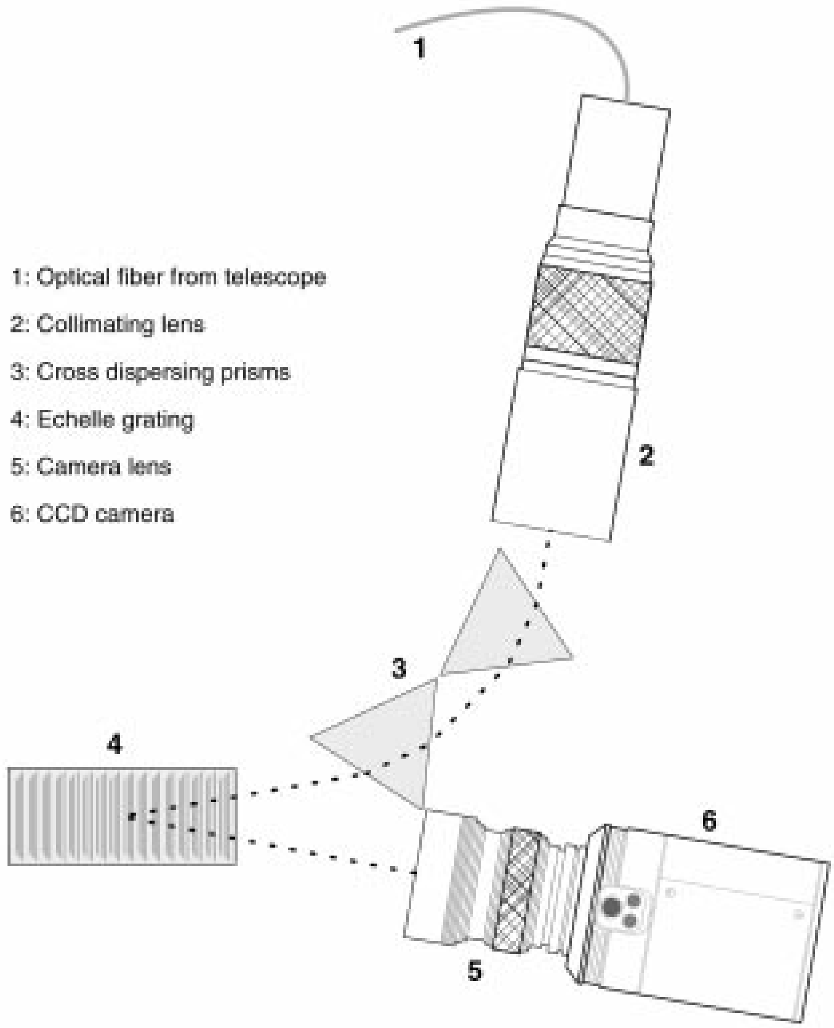

Figure 3. Semi-scale layout of the UQES.

a single-exposure design is to be achieved. Alternative camera optics are currently being investigated. Although initial testing indicated that the existing collimator was adequate, it has been replaced by reflective optics.

5. Conclusions

This paper has been written, not to provide a detailed description of echelle spectroscopy, but to provide 'food for thought'. It is hoped that this has been achieved and that the references provided will provide a basis for further investigation.

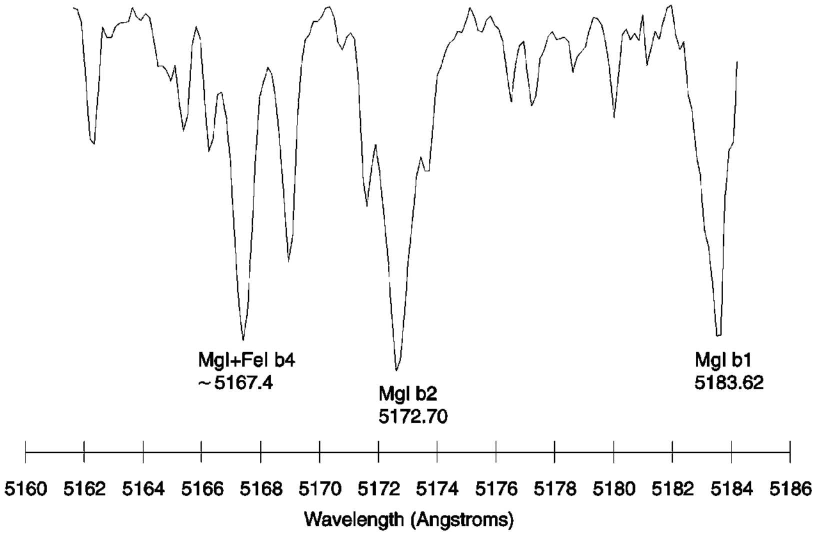

Figure 4. UQES solar spectrum from 5161–5185 Å: Magnesium l iron b lines.

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