A small actively-controlled high-resolution spectrograph based on off-the-shelf components

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ABSTRACT

We describe the design and testing of an in-plane échelle spectrograph based on a double-pass design with the aim to be small and efficient with the minimum number of optical surfaces - currently a camera lens, cross-dispersing prism, grating, an actively controlled mirror and a detector. It is built from catalogue optical components and has dimensions 20×30 cm. It works in the optical regime with a resolution of >70,000 and throughput of 10%. The spectrograph is fed by a bifurcated fibre where the fibre to the telescope is tapered to provide efficient focal reduction of the beam and the other fibre is used to provide simultaneous Thorium Argon or a Tungsten flat field lamp for wavelength calibration. The positions of the arc lines on the detector are processed in real time and commercial auto-guiding software is used to treat the positions of the arc lines as guide stars. The guiding software sends any required adjustments to mechanical piezo-electric actuators which move the mirror sending light to the camera removing any drift in the position of the arc lines. The current configuration provides precision of 1/50th of a resolution element.

1. Introduction

Echelle spectrographs have long been work-horse common-user instruments for large telescopes for a wide variety of scientific endeavours. Instruments such as UCLES (Diego et al. 1988) saw more 30 years of service at the AAT. UVES on the VLT and HIRES on the Keck have both been in service for nearly 20 years and are usually the most in-demand instruments. The scientific importance of such high-resolution spectrographs along with others dedicated to smaller telescopes (e.g., ELODIE and CORALE, APF) has led to a new generation of optical and infrared high-resolution spectrographs for 8-10 telescopes ESPRESSO for the VLTs (Pepe et al. 2018), IRD for Subaru (Kotani et al. 2018), PEPSI for LBT (Strassmeier et al., 2015), MAROON-X for Gemini-N (Seifhart et al. 2018) HPF for the HET (Mahadevan et al. 2018) as well as for 4-m class telescopes EXPRES for Lowell (Fischer et al. 2017), NIRPS for NTT (Bouchy et al. 2017), Veloce for the AAT (Gilbert et al. 2018), Spirou for CFHT (Donati et al. 2018) and CARMENES for Calar Alto (Quirrenbach et al. 2018).

The achievement of meter-per-second radial velocity precision is one of the major technological breakthroughs of recent years. Although this effort can be viewed as driven by the search for extra-solar planets following the discovery of the first such system in the early 1990s (Wolszczan & Frail 1992), the quest for highly accurate radial velocity measurements was actually under development for many decades beforehand.

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The path from the suggestion that stellar velocities might be accurately calibrated (Struve 1952), to solar studies (Becker 1976; Koch & Woehl 1984) to pioneering stellar observations using HF gas cells (Campbell & Walker 1979; Campbell, Walker & Yang 1988) to today’s standards of long-term several m s$^{-1}$ (or short-term sub-m s$^{-1}$) RMS measurements with Keck/HIRES (e.g., Vogt et al. 1994, Butler et al. 1996), ESO 3.6m/HARPS (e.g., Pepe et al. 2000), HET/HRS (e.g., Tull 1998), VLT-UVES (Dekker et al. 2000), and AAT/UCLES (Tinney et al. 2001) is one that leads through several generations of similar spectrographs, detectors, and calibration methodologies.

Although the instruments have not changed dramatically, the ongoing improvements in the production of accurate and precise radial velocities has arisen due to the ability to accurately calibrate spectra, keep instruments stable over a long period of time and to effectively reduce astronomical spectra. However, the large beam sizes of large telescopes has tended to mean that large bespoke optics is required for optical elements and so the optics required tend to be relatively expensive, e.g. HIRES on Keck uses a mosaic of three gratings with a size of 1×4 foot (Vogt 1992). The recently developed ESPRESSO spectrograph cost 12.6MEuros and 131 FTEs.

We contribute to this series of work by investigating some alternative approaches for the configuration of a high-resolution spectrograph. We describe our experiments with a laboratory-based test-bed high-resolution spectrograph using traditional components but aimed at reducing the size and cost without diminishing the performance unduly. This instrument, designated the EXOhSPEC Pathfinder was designed and constructed in the Centre for Astrophysics at the University of Hertfordshire. The goal of this project is to demonstrate new design features which we have implemented to explore our new spectrograph design which might be deployed on a 0.7m telescope or larger.

The article is structured as follows. In section 2 we outline and present the basic spectrograph, considering its design and components. In Section 3 we describe our initial set of components and first test results considering modal noise, temperature, throughput and active stabilisation and in Section 4 we discuss likely future developments for high-resolution spectrographs including a move to adaptive optics and a possible move from CCD to CMOS which will enable smaller more numerous pixels.

2. Preliminary design of spectrograph

The construction of a high resolution spectrograph aimed at measuring radial velocities with no initial budget, required that our pathfinder spectrographs work in the optical regime where detectors, optical equipment and their coatings are much more affordable. Initial versions of the instrument were assembled using existing in-house optical components from undergraduate laboratory experiments or retired or borrowed from other projects. The current version of the spectrograph uses standard optical mounting hardware on an 4×2 foot optical bench. This table is located in an interior lab that has controlled access. The spectrograph, is located in an externally facing laboratory on the College Lane campus of the University of Hertfordshire with black out blinds and suitable darkroom equipment in order that a dark environment can be created as required. In Fig. 1 we illustrate the outline Zemax design of the double-pass spectrograph. In Fig. 2 we illustrate one of our initial implementations of the spectrograph along with the various components of the spectrograph.

\footnote{http://obswww.unige.ch/pepe/Repository/DRD03_Executive%20Summary_VLT-TRE-ESP-13520-0037_Iss3.pdf}
The laboratory temperature control is tied to a central building control system and the ambient tem-
perature of the room is currently rather poorly controlled oscillating over 5deg on a variety of timescales.
We monitor temperature changes at the apparatus with a thermometer. With protective insulation we can
reduce the temperature variations felt by the apparatus considerably but the issue of temperature instability
has encouraged us to investigate novel solutions for control of the spectrograph.

We have arranged the laboratory to be fed by fibre optic cable from a relatively sheltered nearby first
floor flat roof of an adjacent building. There we keep a Celestron 8 inch telescope, with a SkyWatcher EQ3-2
Pro Synscan mount. Although it is in a highly light-polluted area of campus, overlooked on all sides by
office windows, suffers from vibrations caused by a nearby heat exchanger and with a rather restricted view
of the sky it does provides easy access to the Sun, Moon and bright stars when the conditions are sufficiently
benign. We attach a 50 µm FC/PC fibre to the telescope using a Shelyak fibre injection unit (PF0018 F/6
50µm injection unit and M42 T adapter to the telescope).

2.1. Active stablisation

Conventional designs of high precision echelle spectrographs rely principally on good passive athermal
designs and stable mechanical components. Environmental variables such as temperature, pressure and vi-
bration are isolated from the spectrograph by insulation, inert gas filling or vacuum operation and vibration
damping arising from massive and/or highly damped materials. The addition of active control of a few
parameters such as distances between components or deflection angles of certain components can relieve
the need for expensive and/or massive components to achieve the same level of overall stability. An ‘active
metrology’ schemes whereby, for example, the distance between two components is measured with (com-
mercially available) laser interferometers and used to drive a piezoelectric motion transducer to stabilise the
optical distance can offer compensation for both temperature and pressure effects in the spectrometer. With
careful passive design and optimum optical configurations this approach might offer considerable benefit and
potentially offer a retrofit solution to improve the performance of existing spectrometers.

An alternative approach to athermal design and stable mechanical components is consideration of how
to produce a stable spectrum position on the sensor? If a reference spectral source is imaged through the
spectrometer then the position of this (these) source in the dispersed image on the detector can be used to
produce an error signal to drive a component of the spectrometer so that the image remains fixed in position
on the detector. If the object spectrum is imaged through the same optical path then it too is stabilised.
Note that to zeroth order it does not matter what is between the spectrometer input and output. Obviously
it will be good design practice to have a stable optical/mechanical design in order to reduce the range of the
control corrections needed. To first order the spectrum on the detector is stabilised to the limiting stability
of the reference source. The remaining issues for stability will be second and third order effects due to
two principal factors: a) the angle/position of the optical path through the spectrometer will be changing
with the corrections and b) changes in the dispersion of the spectrometer cannot be completely eliminated.
There will be slight difference in the design approach which seeks to minimise aberrations and third order
effects such as the change of dispersion of the lens and prism with temperature and of the surrounding
gas environment. Changes in the dispersion of the spectrometer may be approached in a similar way that
achromatic lenses are designed, i.e. introduction of components which cancel the overall dispersion variations
with temperature or pressure. The two primary requirements for this design are a usable stable reference
source and a control loop with sufficient capability to affect the necessary corrections. Many secondary
design considerations remain to be fully explored.

2.2. Preliminary optical Design

As with most spectrographs the idea is that the end product should have high throughput, dispersion, optical performance, stability and yet be produced for as low a cost as possible. We note for example the exciting new designs afforded by single mode fibres (e.g., Feger et al. 2014 and Crepp et al. 2016) and their feeding by adaptive optics systems (e.g., Jovanovic et al. 2017), the highly promising work of fibre manipulation of a multi-mode fibre (e.g., Calcines et al. 2018, Anagnos et al. 2018), the potential for high resolution integral field spectroscopy (e.g., Lovis et al. 2016) and in general the promise of astrophotonics spectrographs (e.g., Gatke et al. 2019). Some of these suffer from relatively low throughput and/or wavelength coverage due to the properties of single mode fibres and problems of efficiently coupling light into a single mode fibre and so there remain a variety of technical hurdles to overcome prior to turn-key utilisation. Nonetheless, these devices and concepts provide great promise and will likely help to make it appropriate and feasible to have a high resolution spectrograph in space (e.g., Plavchan et al. 2018). Our currently preferred methodology for achieving efficient focal reduction is through tapering of the input fibre from the telescope as proven by Choochalem et al., (2020).

One of the key issues for high precision spectrographs is that they are stable on all timescales which might be of interest for astronomical phenomena which if considering exoplanets is from hours (e.g.) to hundreds of years (e.g.). Both simultaneously calibrated spectrographs such as HARPS and Iodine stabilised spectrographs such as HIRES both work on the premise the optical arrangement should be as stable as possible so in the case of common user spectrographs like HIRES a bespoke calibration procedure is required to ensure that each night begins with ThAr lines falling on exactly the same position on the detector. HARPS achieves this with extreme temperature and pressure control along with complete isolation of the spectrograph from any human interaction.

There are many different successful designs available for us to develop from. We seek to benefit from these and in particular we take inspiration from the HARPS (Pepe et al. 2000) and PFS (Crane et al. 2006) instruments due to their exquisite performance over more than a decade of operation. Both of these designs are themselves derived from several similar previous instruments and so have considerable heritage. Given that we have a laboratory available some distance from any plausible telescope a fibre feed like HARPS was desirable. On the other hand the small size and re-use of optical components provided by a double-pass design was particularly appealing from the PFS design. We first develop some insight into the critical design parameters for the spectrograph.

2.2.1. Finite image size and resolution

Based on an input image size of diameter $h$ and a collimator lens with focal distance $f_c$ and radius $S$. The light rays coming from the edge of the image will not be parallel to the ones from the center of the image and offset by a small angle $\delta \alpha$

$$\delta \alpha = \frac{h}{f_c}$$

(1)
where we assumed that $\tan \delta \alpha \sim \delta \alpha$. This small angle will then propagate into generating a finite size of the final image. The condition on the required dispersion of an element (grating or prism) is that a light ray of minimal wavelength to be resolved has to be deflected an angle $\epsilon$ equal or larger than this $\delta \alpha$. A refocusing lens or camera will only affect the physical size of the image but will not contribute in separating images of different wavelengths further.

Let us compute this angle for an arbitrary echelle grating working at some blaze wavelength (the wavelength at which the incoming angle is equal to the outgoing angle, also called Littrow condition). Based on the grating equation for a general incoming and outgoing ray and where $d$ is the distance between the repetitive grooves or facets in the diffraction grating

$$d(\sin \theta_{\text{in}} + \sin \theta_{\text{out}}) = m\lambda_B$$  \hspace{1cm} (2)

Gratings are usually most efficient when working in the Littrow configuration. That is, the incident rays are perpendicular to the facets of the grating. In this situation there is always an integer number of wavelengths that are exactly reflected back with $\theta_{\text{in}} = \theta_{\text{out}}$ which we call blaze wavelengths ($\lambda_B$). The dispersion around these blaze wavelengths can be treated as a small perturbation, so the properties of the dispersion around $\lambda_B$ will define the performance of the spectrometer in terms of its resolving power. For a $\lambda_B$ and a slightly different $\lambda_B + \delta \lambda$, one can write

$$d(\sin \theta_B + \sin \theta_B) = m\lambda_B$$ \hspace{1cm} (3)

$$d(\sin \theta_B + \sin (\theta_B + \epsilon)) = m(\lambda_B + \delta \lambda)$$ \hspace{1cm} (4)

Expanding in powers of small $\epsilon$ around $\theta_B$ the difference between (3) and (4) leads to

$$\epsilon = \frac{m \delta \lambda}{d \cos \theta_B}$$ \hspace{1cm} (5)

where $m$ is the diffraction order, $\lambda_B$ is the central blaze wavelength and $\theta_B$ is the blaze angle of the grating. To distinguish $\lambda_B$ from $\lambda_B + \delta \lambda$, the small angle $\epsilon$ must equal the one caused by the finite size of the input image, leading to the condition

$$\epsilon = \delta \alpha$$ \hspace{1cm} (6)

By substituting the relations for $\delta \alpha$ in Eq.(1) and for $\epsilon$ in Eq.(5), we get

$$\frac{h}{f_1} = \frac{m \delta \lambda}{d \cos \theta_B}$$ \hspace{1cm} (7)

This expression can now be re-arranged to find out the size of the first collimating lens (and therefore the size of the grating) by applying three definitions,

- **Resolving power** $R$ is an adimensional number defined as $R = \lambda/\delta \lambda$, and quantifies how well a spectrometer can discriminate wavelengths. A high resolution spectrometer for stellar studies and exoplanet searches should have need a resolving power $> 5 \times 10^4$ ($R > 10^5$ desirable). Moderate resolutions between 1000 – 20000 are typically sufficient for spectral classification and cosmological studies, and anything below 1000 is considered low-resolution.
• **Opening angle** $a$. The beam input of the telescope is usually specified by its opening angle $a$. The tangent of this opening angle is the ratio between the radius of the collimator $S$ and its focal length $f_1$ ($\tan a = S/f_1$). Using this definition and substituting for $\delta \lambda$ Eq. (7) becomes

$$S = Rh \tan a \frac{d \cos \theta_i}{m \lambda_B}.$$  

(8)

• **Numerical aperture** $N$ is defined as $N = n \sin a$, where $n$ is the refractive index of the medium after the fibre. For vacuum applications $n \sim 1$, so the tangent of the opening angle $a$ can be written in terms of $N$ as

$$\tan a = \frac{N}{\sqrt{1 - N^2}}.$$  

(9)

We can now write $S$ as a function of the design parameters ($R$ and $N$), obtaining

$$S = Rh \frac{N}{\sqrt{1 - N^2}} \frac{d \cos \theta_i}{m \lambda_B}.$$  

(10)

For most practical cases, e.g., a typical fibre with $N \sim 0.22$ one can simplify to

$$S = Rh N \frac{d \cos \theta_i}{m \lambda_B}.$$  

(11)

In an astronomical spectrograph the resolution is estimated from the FWHM of the instrumental profile, which in our case is the image of the entrance slit (or fibre). For a Gaussian profile, the FWHM is $2.35 \sigma$, where $\sigma$ is the square of the variance of the profile. For a box shaped profile of size $h$, its variance is $\sigma^2 = \frac{h^2}{12}$, so the effective $h$ is to be used is $2.35\sqrt{\frac{12}{12}} h_r = 0.67 h_r$, where $h_r$ is the width of the slit (or fibre). By numerical substitution of the parameters for the HARPS spectrometer ($R \sim 10^5$, $\lambda_B = 550$ nm, $m = 100$, $\theta_B = 75$ deg, $d = 1/32$ mm) one obtains a beam diameter of $2S \sim 20$ cm, which matches the specifications listed in the instrument description 2.

2.2.2. **Invariant grating relation**

One more relation can be derived that is useful for spectrometer design. The right factor on the right-hand-side of (11) depends only on grating parameters. For example, we would like to know the diffraction order at which we need to work given some groove density and wavelength. In Littrow conditions, the diffraction order $m$ can be derived from eq. (3) as

$$m = \frac{2 d \sin \theta_B}{\lambda_B}.$$  

(12)

which we can substitute in Eq. (11) to obtain

$$2S = \frac{10.67 h_{\text{real}} R \ N}{\tan \theta_B}.$$  

(13)

2http://www.eso.org/sci/facilities/lasilla/instruments/harps/inst/description.html
Table 1: Beam diameter, grating length and ruled area requirements for several representative grating parameters. Given that resolutions over 50 000 are always needed, the ruled area (cost and complexity scale with this) can be dramatically reduced by reducing the input image by fibre reformating. The first line of the table is given in bold and are the effective sizes of the HARPS grating mosaic which is comprised of two gratings mosaiced together to give a total area of $84 \times 21.4$ cm.

<table>
<thead>
<tr>
<th>Resolution $\lambda/\delta\lambda$</th>
<th>$h_r$ [µm]</th>
<th>$NA$</th>
<th>$\theta_B$ [deg]</th>
<th>Beam diameter $2S$ [cm]</th>
<th>Grating length $l$ [cm]</th>
<th>Ruled Area $A_r$ [cm$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^5$</td>
<td>50</td>
<td>0.22</td>
<td>75</td>
<td>19.7</td>
<td>76.0</td>
<td>1498</td>
</tr>
<tr>
<td>$10^5$</td>
<td>10</td>
<td>0.22</td>
<td>75</td>
<td>4.0</td>
<td>15.2</td>
<td>60.8</td>
</tr>
<tr>
<td>$10^4$</td>
<td>50</td>
<td>0.22</td>
<td>45</td>
<td>73.7</td>
<td>104.2</td>
<td>7679</td>
</tr>
<tr>
<td>$10^3$</td>
<td>10</td>
<td>0.22</td>
<td>45</td>
<td>14.7</td>
<td>20.8</td>
<td>306.3</td>
</tr>
</tbody>
</table>

where the $2S$ is the diameter of the first collimator lens (and diameter of the beam). Note that the dependence on the groove separation and wavelength have both disappeared. This means that there are always an infinite number of combinations of groove density, wavelength and working diffraction order that can achieve the same resolution for a given beam size. For example, we can work at low groove density (eg. 32 lines/mm) and high diffraction order (say $m=100$) or at a low diffraction order ($m=1$ and high groove density (3200 lines/mm) and still achieve the same resolving power. $2S$ is the diameter of the collimator, which is the deprojected size of the grating for a given angle $\theta_B$. Assuming a rectangular grating, its height (along the grooves) is $2S$ and its length is $l$. Using basic trigonometry, one finds that the length $l$ is related to the blaze angle and the beam diameter by $l \cos \theta_B = 2S$, which leads to

$$l = \frac{0.67 \ h_{\text{real}} \ R \ N}{\sin \theta_B} \quad (14)$$

so the total ruled area $A_r$ is

$$A_r = lS = (0.67 \ h_{\text{real}} \ R \ N)^2 \frac{\cos \theta_B}{\sin^2 \theta_B} \quad (15)$$

Table 1 shows the required grating sizes for some example spectrometers (eg. HARPS-like). Classic echelles work with low groove densities to obtain many overlapping orders (which is another design issue not discussed here) but the actual resolution has nothing to do with that, as it could be achieved with higher groove densities working at lower diffraction orders.

3. Spectrograph components

We layout the spectrograph component choices based on our tests and design considerations presented in the previous section.
3.1. Echelle grating

Using our preliminary optical design ideas specifically with the development of our laboratory spectrograph in mind we can rearrange, (13) using the diameter of the beam, $D$ instead of $2S$ to obtain and noting that for a fibre fed instrument $h_{\text{real}}$ is the diameter of the fibre,

$$R \leq \tan \theta_B \frac{D}{h_{\text{real}}} N$$

Taking the HARPS spectrograph we might hope to emulate its resolution and approximate optical characteristics by using a grating with a similar blaze angle and ensuring that the numerical aperture of the beam is preserved say when moving from a 3.6m telescope to a 0.7m telescope by rescaling the size of the input beam accordingly by a factor of five ($3.6/0.7$). Although this might be an undesirable thing to do due to geometrical optics meaning leading to the a loss of light proportional to the change in area of the beam size (e.g. Haynes et al. 2017). Based on the work of Choochalerm et al. (2019) we can use graded index instead of step-index fibres and reduce this beam size by a factor of 5 with a factor of two efficiency loss allowing us to reduce the size of the required echelle grating. For example, in HARPS they deploy a grating mosaic to give dimensions of 84.0×21.4 cm. Reduction of size of the grating by a factor of five fits approximately with available off-the-shelf gratings like the Newport 53114ZD01 with dimensions: 6x15cm for a few thousand dollars or with reduced resolution using the volume produced Thorlabs GE-2550-0363 with 31.6 grooves/mm, 63deg blaze, 2.5 cm x 5 cm (×9.5 mm thick) for a few hundred dollars. The echelle is mounted facing downwards in order to minimise exposure to dust.

The brings a consequent reduction in the size of the lens and cross-disperser optics to the scale of standard catalogue components and in particular the utility of standard telescope lenses. While this has the potential to yield very significant cost savings and clarity of performance due to using well-characterised mass produced components, there are a number of issues that might arise from doing this. For example, the camera optics do have to be of high quality in order to keep the aberrations smaller than the fibre image size. In order to investigate these and many potential other issues we have built several prototypes.

3.2. Collimator, Camera Lens and Cross Dispersing Prism

The spectrograph optics are used in double-pass and so act both as collimator and camera. The required optics are all spherical. Our setup has thus far been with off-the-shelf camera lenses (such as the 200mm Vitkar lens shown in Fig. 2) or the achromatic doublet collimator and focussing lenses (with 650-1050 nm coatings, AC254-050-B and AC254-200-B).

We place an optical stop external to the lens system and is positioned at the distance to the center of the diffraction grating, i.e., beyond the cross-disperser. Camera focus is checked in a variety of ways using by-eye checks of calibration spectra. For example, ensuring robustness to blocking half of the collimated beam. In focus, spectral lines should show no discernible shifts.

In our double-pass configuration, the quality and performance of this lens is rather critical. Any significant misalignment or chromaticity is easily seen in the output spectra. For example, it can be seen on the left-hand side of Fig. 4 that the current camera layout suffers from some coma. This variation of the spot shape over the camera field imposes a limits on the resolution and achievable radial velocity precision in
our system due to the limited number of calibration lines. We have done some Zemax calculations and find that this is in line with the expectation for such a lens. Details of which are presented in detail in Lhospice et al. and Kawinkij et al. (2019). We also have a separate project to develop a bespoke highly corrected small double Gauss lens which is laid out elsewhere, Baker et al. (2019). While this limits the utility of our current setup, this implementation was judged sufficient for our initial tests.

We use an equilateral dispersive prism in order to cross disperse the beam. We have used a few different BK7 prisms and now use an N-BK7 anti-reflection coated 60deg prism (Thorlabs PS854 - F2 50 mm). In principle a VPH grating (e.g., Seifahrt et al. 2018) would offer higher throughput, in the development stage prisms are easy to handle offering a variety of dispersions, sizes and coatings and are readily available.

3.3. Detector and Control System

A key driver in spectrograph design is the detector. The HARPS detector choice of two EEV type 44-82 CCDs with 15µm pixels leads to a pixel oversampling of around 4. These relatively large pixels and apparently excessive oversampling are a key element in the success of HARPS in the sense that it can utilise CCDs where every pixel produces high dynamical range and that the point-spread function is always fully sampled and far less prone to detector inhomogeneities and irregularities (e.g., Butler et al. 2019). In order to match these characteristics we need a large format camera with 3µm pixels. Suitable such cameras may be available shortly, see Section 10. In the meantime, we use a QSI 532ws-M1 camera. This has 2184×1472 6.8µm pixels and enables 72 orders with a wavelength coverage from 4650–8890 with a resolution 0.015 – 0.022Å/pixel. In operation the detector has a gain of 1.1 e-/ADU and a typical read noise of 10 e-. Tests have shown that there is slight non-linearity of the detector which fit with a quadratic becomes within 1% of linear for ADU counts below 6×10^4, which is our operational limit. The camera is air cooled and is typically run at ~30°C from MaximDL. We note that even when comfortably within its maximum cooling it can take over an hour for the temperature to stabilise. In order 40 the object and reference fibre are separated by approximately 15 pixels and different orders by 30 pixels from one another. Different spacings and numbers of orders can readily be achieved by using different cross-dispersing prisms.

3.4. Spectrograph setup and alignment

In order to align our spectrograph we follow the following sequence of steps: (1) Use a green laser diode (e.g., Thorlabs CPS532 Laser diode module, 532nm) to set up a straight path (same height, along a row of holes in the optical bench). (2) Put in the prism and rotate it and align so that the reflected/transmitted light doesn’t change height. (3) Put in the lens, adjust height, position, and angles so that all reflections of the lens hit the laser. (4) Find the minimum deviation angle of the prism: when rotating the transmitted spot moves. (5) Put in the grating so that the spot hits approximately the centre of the grating and rotate it so that the reflected orders are approximately in the plane of the laser. (6) Put in the fibre holder, so that the laser passes through the center. (7) Attach the fibre with a red laser diode (e.g., Thorlabs CPS635S Laser diode module, 635 nm) and find the focal spot (the spectrum of the laser diode is in focus at the fibre end). (8) Move the fibre 2mm out of the centre. (9) Centre the grating and check that the reflection hits the reflection grating. (10) Centre the spectrum on the camera. (11) Put white light through the system to focus the camera. A rotation of the camera might be necessary. (12) For the red and central orders the fibre was moved and then the position of the camera measured, when the lines were back in focus. The average
focus offset between the two areas is 0.70mm. The reflective grating was adjusted so that both blue and red orders had were in focus at approximately the same position.

3.5. Data Reduction and Analysis

The spectrograph data reduction system has been written in python specifically for the flexible reduction of cross-dispersed high-resolution data and that its order tracing is as flexible as possible in order to accommodate a variety of different components and setup’s. For example, the software is designed to cope with a variety of resolutions, order separations, overlaps and curvatures as well as over/under sampling. It can be used with any type of calibration source once an initial wavelength solution has been identified through the identification of known wavelength spectral lines. The philosophy has been that once a wavelength solution exists for one configuration a new nearby solution might be found relatively easily given knowledge of the expected known wavelength spectral lines. The data reduction software known as HIFLEEx is available on github and described in Errmann et al. (2019).

3.6. Fiber Input and Modal Noise

We introduce light into the spectrograph by means of two 10µm fibres one of these fibres is for the target and the other is for the reference source. This is achieved with two 10µm core 0.1 numerical aperture multimode fibres (Thorlabs FG010LDAFBUNDLE) supplied by Thorlabs as a “custom 1×2 fanout bundle” from their range of bifurcated fibre bundles. Each fibre is contained in a protective jacket (Thorlabs FT061PS). These two fibres are combined in a common end connector jacket (also inside FT061PS protective cable) which is connectorised with common end connectors (FC/PC, 30260G3). The reference fibre is connected directly into ThAr or Tungsten flatfield lamp. The target fibre is usually connected into a Fiberbench Beamsplitter Module (Thorlabs FBT-50NIR- 50:50) which allows for flexible connection to sky fibre or another calibration source. We find that the fibres used (FG010LDA) have a peak throughput of 75% measured in Choochalerm et al. (2019) where we measure the absolute throughput of fibres as part of our fibre characterisation experiments.

We can get light from the Sun into the laboratory by imaging onto a 5 mm ball lens with a 10° field of view (Thorlabs 43-412) connected to a 15-m long 50µm graded index 0.22 numerical aperture FC/PC cable (Thorlabs M42L15). The large field of view of the ball lens means that tracking errors should not compromise obtaining integrated solar disk light. Unfortunately, we found that the field of view was so large that light scattered by nearby clouds noticeably degraded the quality of our signal and so observations were only attempted when skies were mostly clear. Clouds that do not uniformly cover the Sun during an integration can lead to a significant solar rotation residual since the variation in the velocity across the disk of the Sun is 2 km/s.

We have found that in our instrumental setup, modal noise can be a significant issue. It can be a strong function of wavelength, temperature and even caused by the small agitation induced for example by the laboratory air conditioning fans. In the upper plot of Fig. 5 with appropriate scaling and zooming, modal noise can for some wavelengths even be seen in raw data from the camera. The upper plot of Fig. 5 presents an illustration of the wavelength dependence of the problem. The issue of modal noise is a well known one for high resolution spectrographs and has been examined in substantial detail and there are a number of potentially mitigations that may be made though no “silver bullet” (e.g., Ishizuka et al. 2016; Petersburg...
et al. 2018; Blinda, Conoda & Wildi 2017). One of the best options would appear to be the appropriate agitation of the fibre in order minimize the effects of modal noise. While we did find this effective our available mechanical solution introduced unwanted vibrations into the setup. Thus instead we deploy an optical solution to the problem by using a mirror galvanometer system.

The idea of the 2D galvo system with silver coated mirrors (Thorlabs GVS002) is along with a function generator (Tektronix AFG1022) to apply appropriate patterns of frequencies and amplitude in order to apply a small movement to the beam so that the beam position is changed slightly and thus the illumination of the fibre carrying the light to the spectrograph is altered. We typically use this in 10-100 Hz range with voltages of 20–50 mV. In Fig. 6, the top plot shows a schematic of the arrangement used to test the impact of modal noise, the middle plot shows the reality on the optical bench of the different components and the lower plot illustrates the improvement available by modulation of the beam. While this system is effective, we note that in order to optimise the reduction in modal noise we need to introduce very significant movement of the beam which then causes a significant loss of throughput. In the case of this plot by a factor of about two and so this system requires further optimisation.

3.7. Calibration

For order tracing and flat fielding we use a stablised Tungsten lamp (Thor Labs SLS201L/M). Initially we used a so-called “high intensity fiber light source” (Thorlabs OSL1-EC), however, this lamp had rather limited red throughput. The relative system efficiency of the Tungsten lamp along with the camera and fibre throughput can be seen in Fig. 3 which illustrates the overlapping spectral orders provided using the flatfield lamp but given the strong decline in efficiency towards blue and red spectral orders means that multiple flat fields must be taken in order to take good quality data in these regions. We found that although the colour of the lamp is relatively stable, the intensity of the lamp drops by approximately 10% during the first 30 minutes after switching it on.

For wavelength calibration reference we use a Thorium Argon lamp (P858A - hollow cathode lamp - Thorium with Argon gas fill from Photron). This typically gives several thousand usable calibration lines across the optical regime, e.g., Fig. 4 shows lines identified from the reference catalogue (in red) used to create the wavelength solution. The remaining lines of the reference catalogue, not used for fitting the solution are shown in green. In the red optical regime a greater line density would be available by using the larger line density available from a UrNe lamp (e.g., Ramsey et al. 2007) and indeed the output from ThAr and UrNe might easily be coupled together. However, it is likely that the development of laser combs and perhaps particularly by devices like the Betters et al. (2016) photonic comb will be the most appropriate calibration.

In order to check the stability of the bifurcated fibre arrangement, we split the light from the ThAr lamp into two beams and feed the target and calibration fibres separately with the same lamp. Fig. 7 show the measured difference in radial velocity between the target and calibration fibres over a 24 hour period. We used 10 second exposures with a 10 minute cadence. No drift between the two fibres is apparent with an RMS of 20.
3.8. Active Stabilisation

The beam is turned through 90deg toward the camera using a right-angle prism mirror (Thorlabs MRA20-G01). It is mounted on an XY translation stage consisting of a Kinematic Mount (KM200T - SM2), a Kinematic Prism Mount (KM200PM/M) and a Reflecting mirror Mount (KM200CP/M). Its position can be adjusted by piezo inertial actuators (Thorlabs PIAK10) which offer movements of 20 nm and “no backlash” in a compact package.

Our active stabilisation system uses telescope guiding software (Maxim DL) to detect the position of a ThAr line and this “star like” reference image is used as a “guide star”. The ThAr image position on the CCD detector is then used to control XY actuators (Thorlabs) on the turning mirror to stabilise the spectrum of the object on the CCD. Fig. 8 shows a screen capture of the control computer, the camera control window in the top right indicates among other things that the image (an arc line) is being tracked and indicates the camera information along with centroid displacement of the image. The other windows monitor the image. In the top left is the image that is being tracked along with a circular apertures for which statistics are reported in the top middle window. The lower right window indicates the corrections made by the actuator based on the errors of the centroid reported in the camera control window. The bottom left plot shows the centroid behaviour in x and y with no tracking and then once tracking has been switched a fairly rapid adjustment of the centroid position to the chosen baseline.

Our current version of the spectrograph is very much a prototype attempting to demonstrate functionality and achieves the expected resolution, wavelength coverage and image quality that we expect. One of the key facets of a radial velocity spectrograph is long-term stable temperature, pressure and humidity and to this end modern spectrographs routinely work at ±0.01K, ±X Bar and a fixed humidity. In Fig. 9 we show how the sensitivity of our prototype reacts to temperature fluctuations. In the upper set of plots, we illustrate the importance of ambient temperature and relative humidity as measured on top of the nearby switched-off flat field lamp. The top two plots measure the pixel change in centroid in x and y on the centroid of a ThAr line relative to the lower two plots showing the temperature and humidity and pressure, measured on top of the switched-off flat lamp. The temperature variation happens 60 s after the humidity changes. The humidity and introduction of the offset are strongly correlated. In the lower set of plots the x and y pixel offsets as measured by the tracking routine (full frame) and the temperature measured at different places of the room. These measurements were made while the CCD was reaching steady state and it can be seen that the temperature of the camera casing varied independently of the room and grating temperatures and that the offset of the spectrum is correlated with the temperature of the camera casing.

The guiding loop to control the actuators is written in visual basic using the .Net APIs and uses the Visual Studio along with the guiding function of MaximDL. This can be used in single or multi-guide star mode. Maxim DL allows a variety of different functionalities of guiding from automated single or multi-star to fully defined by the user. MaxIm DL is used in single or multi-star autoguiding mode to capture the images and measure the positions of the “guide stars”. The guiding loop to control the actuators is written in C# using the Thorlabs Kinesis .Net APIs and uses MaxIm DL’s COM interface to access the guiding errors as the input to a PID control loop. The errors are dependent on the exposure (signal to noise) so optimisation of time constants is required. Our current implementation of the loop uses kp proportional terms (x=10, y=20), kp integral (steady state error) terms (x=0.2, y=0.2), kp derivative (dampening) terms (x=0.1, y=0.1), an iMax limit for integral to prevent wind-up of $x + y = 1$, and a Minimum Move of $x + y = 2$. The current system can be stabilised to within 0.01 pixels during large temperature and mechanical changes. Our attempts to take this on-sky have been rather hampered by local conditions. 2019 June 27th we
took some relative poor quality signal-to-noise/pixel≈30 observations of the Moon over a 20 minute period obtaining an RMS of 14 m/s.

3.9. Detector choices - CCD versus CMOS

As previously mentioned the detector is a key element in the success of a spectrograph. The excellent properties of CCDs in particular high sensitivity, linearity at 0.2% level and large dynamical range have made them the ubiquitous detector of choice. While these devices have excellent performance characteristics the range of applications that they are used for is relatively limited and so professional astronomical grade CCDs sold by companies such as Teledyne (E2V) have a unit costs of around 100k dollars each. The ensuing high cost / low demand for their performance capabilities means that the ongoing development of CCDs appears in have slowed in the last decades. On the other hand an alternative image recording technology CMOS has seen a huge increase in demand driven by their fast read-out and relatively low cost per pixel relative to CCDs. Traditionally CMOS devices have had a number of significant drawbacks for astronomical purposes. In particular, rather high read noise and dark current as well as relatively small pixel sizes and consequently small well depths. We acquired a refurbished Photometrics Prime BSI sCMOS, with the “s” an abbreviation for “scientific grade”. The low-noise and negligible read time gives this excellent performance in a laboratory setting. However, the initial firmware provided does gives rise to significant non-linearity because of the use of two amplifiers to produce the 16-bit output, see Fig. 10. It is expected that a firmware update will address this issue. Other companies such as Andor use a three amplifier scheme in an effort to provide robust linearity throughout the sensitivity range. Andor also provide sCMOS cameras with global as well as more standard rolling shutters found in sCMOS cameras. Despite improvements in manufacturing, it is not clear that concerns about various sCMOS issues have been fully addressed (e.g., Zhan, Zhang & Cao 2018). However, some of these scientific CMOS devices devices are being deemed as mature enough to be used for future space missions such as JUICE (e.g. ESA 2014). Compliance with the significant scrutiny appropriate for selection for space-based scientific imaging missions can be expected to drive further innovation and improvements in manufacturing and camera capabilities.

One of the state-of-the-art CCDs is the E2V CCD 290-99 which has been chosen for use in the high resolution spectrographs ESPRESSO, PEPSI, EXPRES and MAROON-X which all use one or more of these 9216×9232 CCDs with 10μm pixels, read-out-noise of <5 e−, well depth of 90000 e− and a fast read-out achieved by using its 16 output ports. The raw specification for these CCD devices is impressive though comparison with the HARPS CCDs from approximately 15 years earlier has led to an approximately fivefold increase in the number of pixels for an individual device, a reduction from 15 to 10 micron pixels for similar well depth — gain — read-out noise configurations, improved quantum efficiency by around 10% (over the relevant wavelength range) with apparently similar linearity, charge transfer efficiency and cosmetic properties (Cavadore et al. 2001; Calderone et al. 2016). On the other hand, the potential scientific capabilities of CMOS devices appear to have evolved from high noise devices with poor cosmetics to potentially becoming more competitive with CCDs. For example, 150 Mpixel devices with 3.76μm pixels with 16 bit sensors and 44000 e− well depth and single electron read-out-noise are available in the wider commercial market for a wide variety of applications. Apart from the potential for considerably lower cost, the potential advantage of these devices for small spectrographs is that they might offer good performance and sampling while minimising the detector size and the necessity to unduly expand the beam potentially making best use of adaptive optics systems (e.g., Jovanovic et al. 2017). We look forward to further quantification and inter-comparison of new devices.
4. Conclusion

The process of building a small spectrograph using commercially available components has been an evolution of all components moving from (1) a replica grating from Thorlabs to larger more efficient Richardson one, (2) inactive to active control with second order correction, (3) standard input fibre, to birfurcated fibre fed by tapered fibre, (4) iteration of prisms for improved anti-reflection coating and appropriate cross-dispersion properties, (5) control of modal noise through introduction of a galvanometer and (6) recent introduction of a CMOS camera, (7) a variety of Ebay camera lenses to an achromatic triplet (Lhospice et al. and Kawinkij et al. 2019) and/or double Gauss lens (Baker et al. 2019). We have explored that each system works satisfactorily and this has enabled us to obtain a resolution 70000 and throughput of 10% and active control at the 0.02 pixel level. We have demonstrated a small spectrograph can achieve reasonable efficiency, resolution and stability. We have implemented a number of alternative solutions to long standing problems with some success. There are a number of reasons to believe that considerable improvements are possible and that in the future such spectrometers might offer performance, implementation, multiplexing and cost benefits.

5. Acknowledgements

We are grateful for support of this project through a Newton fund grant from STFC (ST/P005667/1 and ST/R006598/1) and to John Collins for his donation of his Celestron Edge HD to the project.

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Fig. 1.— The optical layout from a Zemax model is illustrated. The figure is a top view in the plane of the echelle dispersion. The black outlines are schematics of the optical components.
Fig. 2.— The image shows the layout of instrument on the bench. Following the light path the fibre input (orange) is towards the top-left, it passes through the camera lens top-middle, the cross dispersing prism top-right, grating middle-left. The light then returns by almost the same path and is reflected by the pickoff prism mirror immediately before the camera in the bottom-left. The lower images show the individual optical components from left to right: fibre input (on the right-hand side with red, gold and black piezo actuators above and below and also showing camera lens on left-hand side), camera lens - Vivitar, 200mm f3.5 telephoto lens, cross-dispersing prism (and camera lens), grating, pickoff mirror (a silvered prism, with camera lens to the left and detector to the right illuminated with laser diode diffraction spots).
Fig. 3.— The plot shows overlapping spectral order producing using flatfield lamp.

Fig. 4.— The image shows a CCD image (log10 gray scale) of a tungsten calibration lamp showing the continuous orders of a flatfield lamp simultaneously fed by a ThAr calibration lamp. The right-hand image is a composite of an image from HARPS on the left and the right is from our spectrograph. The ThAr lines are identified from the reference catalogue (in red) and used to create the wavelength solution. The remaining lines of the reference catalogue, not used for fitting the solution are shown in green.
Fig. 5.— The plots illustrate the impact of modal noise on the spectra. The upper plot shows a zoom in of a raw frame where the trace of spectrum (in white and grey against black background) can be seen as apparently periodic features of substantial strength when the spectra are scaled appropriately. These periodic features can more readily been seen in the extracted spectra. The middle plot shows spectral extractions of different wavelength regions: (blue, 900 nm), 15 (orange, 760 nm), 30 (green, 6500 nm), 45 (red, 570 nm), 60 (violet, 510 nm), 75 (brown, 460 nm). The lower plot shows a zoom in on an iron line (FeI at 6678 Å) in the Sun prior to wavelength correction by ThAr where the fibre illumination has been adjusted so as illustrate the potential impact of modal noise on a spectral line.
Fig. 6.— The upper image shows the schematic layout of the spectrograph with galvanometer, the middle image shows the galvanometer on the bench (immediately above the written galvanometer label) and the lower plot gives an example of the impact of modal noise with and without the galvanometer operating.

Fig. 7.— Mean difference between target and calibration fibre over one hour when both fibres are fed by the same lamp with a 3 degree temperature fluctuation.
Fig. 8.— Screen capture of the control computer showing the feedback system in operation. The main frame shows the raw CCD frame with a flat field lamp (a Thorlabs OSL1-EC with low red throughput enabling arc lines to be easily seen) and ThAr both in the target fibre. The camera control window in the top right indicates among other things that the image (an arc line) is being tracked (as a guide star) and indicates the camera information along with centroid displacement of the image. The lower left window indicates the corrections made by the piezo actuators based on the deviations of the centroid reported in the camera control window. The bottom right plot shows two separate plots of the displacement of the arcline in $x$ and $y$ with time. Once tracking has been switched on a fairly rapid adjustment of the centroid position occurs to bring it to $(0,0)$. 
Fig. 9.— The plots illustrate the sensitivity of the system to temperature fluctuations. In the upper set of plots, we illustrate the importance of ambient temperature and relative humidity as measured on top of the nearby switched-off flat field lamp. The top two plots measure the pixel change in centroid in $x$ and $y$ on the centroid of a ThAr line relative to the lower two plots showing the temperature and humidity and pressure, measured on top of the switched-off flat lamp. The temperature variation happens 60 s after the humidity changes. The humidity and introduction of the offset are strongly correlated.
In the lower set of plots the $x$ and $y$ pixel offsets as measured by the tracking routine (full frame) and the temperature measured at different places of the room. These measurements were made while the CCD was reaching steady state and it can be seen that the temperature of the camera casing varied independently of the room and grating temperatures and that the offset of the spectrum is correlated with the temperature of the camera casing.

Fig. 10.— Linearity of the Photometrics PrimeBSI camera shown in the left-hand plot for the full well depth and in the right-hand plot for the flux range between the two amplifiers. The flux was measured in the central 48x48 pixel sized area for different exposure times (black dots). For each exposure time, five flat field images were taken and then normalised and median combined. A linear fit was applied to the data points (grey line). The non-linearity shows the deviation of the data points to the linear fit, scaled by the flux.