Spectroscopy

Introduction

The aim of this project was to construct a spectrograph that allows to undertake a completely different variety of astronomical activities at the serious aficionado level. Being well aware that the astronomical information has basically been obtained through this essential tool, the author had long envisioned its construction, not as a prime goal but just as a means to an end to let him embarking upon new researching activities.

This project report will begin with a succinct analysis of the fundamental concepts of spectroscopy and a brief description of the variety of spectroscopes that so far have been constructed, followed by the analysis of the equations that governs their performance.

Next, the detailed design of a fiber-fed grating spectrograph will be presented, including all its expected parameters in order to allow their lately comparison to the resulting ones. Whatever coincidences or discrepancies arise, they will be a conclusive proof about the carefulness and overall precision managed during the construction process.

The calibration of the spectrograph and its evaluation at field working in conjunction with a 20-cm telescope will be presented. Finally, the spectral type classification of some first magnitude stars will be attempted as an evaluation of the instrument's capability. An appraisal of the overall potentiality of the spectrograph will conclude this report.

Spectroscopes

Spectroscopy is based on the fact that chemical elements can only vary their energetic levels by exact amounts, which are characteristic of each atom. The process of energy emission or absorption implies that atoms emit or absorb photons at some particular and intrinsic wavelengths, according to *Planck's law*:

$$\lambda = hc/\Delta E$$

where h is *Planck*'s constant, c is the speed of light, and ΔE is the change in energy.

Hence, each time a photon is either emitted or absorbed there is a theoretical possibility to determine the exact *"identity"* of the element that has been involved in such process, just by measuring the wavelength of the corresponding photon and thus finding out the involved energy change which finally disclose it[1]. The wavelength of those photons does not depend on any distance at all, just in the related energy change.

The emission or absorption of photons implies abrupt changes in a diagram that plots the electromagnetic radiation versus wavelength for the considered source (called its *spectrum*), respectively arising or lowering its level in narrow spikes generally known as *"spectral lines"*[2]. The basic principles governing this phenomenon are known as *Kirchoff's laws*.

Therefore, in order to firstly detect spectral lines and then measure their corresponding wavelengths, it is necessary that the incoming electromagnetic radiation -which normally spans a wide wavelength range- must be previously *"spread out"* as much as possible. This is what spectroscopes do: *just disperse light to facilitate the detection and measuring of spectral lines.*

To disperse light, practical spectroscopes are based on two different optical principles: the *differential refraction* obtained from a glass prism, or the *interference* obtained from a diffraction grating[3]. Prisms have drawbacks due to their intrinsic *light-passing-through* condition, like as only a limited range of dispersions are possible, its light dispersion is non-linear, and large units are expensive. Those difficulties have made that prism spectroscopes are not longer used, being definitively replaced by grating spectroscopes.

Technically, the name *spectroscope* refers only to the instrument where the final detector is just the eye of the observer, to differentiate it from the case where an imaging system (nowadays always a CCD) is used, becoming properly called a *spectrograph*.

Modern spectrographs mostly use diffraction gratings. There are two basic forms of them: *transmission gratings* (they consist of close and regular spaced grooves in a *transparent*

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[1] Although the task will imply a very careful analysis because of the tremendously large number of possible transitions (only hydrogen, the simplest element, has more than 200 permitted energy levels in interstellar space).

[2] Those lines are never infinitely sharp due to several factors, such as the kinetic Doppler broadening, the quantum broadening, the collision broadening, and the Zeeman effect, among others.

[3] Although quite uncommon, there is also a third possibility which results from the combination of both principles obtained from a "grism" (a prism with a transmission grating in one face).

substrate of quality glass), or *reflection gratings* (they have close and regular spaced grooves ruled in a *reflective* substrate). The physics and mathematical treatment of both types is almost the same, so here up on it will be considered only the reflection grating case.

The ruled grooves make that an incident beam actually becomes reflected and also diffracted at different angles, called *diffraction orders*, as Figure 1 shows. By modifying the shape of the grooves, like making it "saw-tooth", the grating can reflect in the direction of a selected order and thus making the grating to work far more efficiently at that diffraction order.

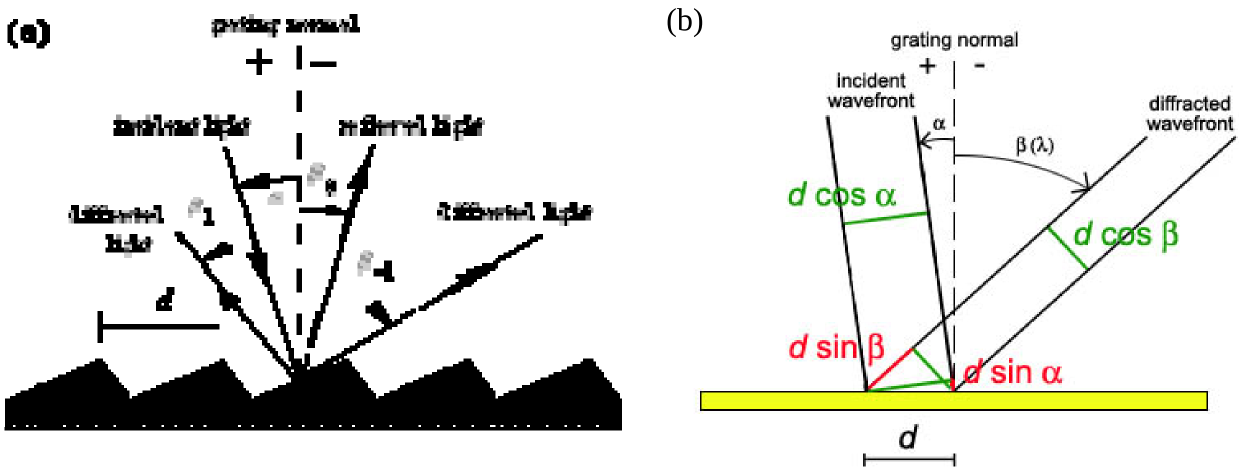


Figure 1
A reflective blazed grating, where the triangular grooves come out of the page
(a) incident, reflected and diffracted rays (just orders +1 and –1)
(b) the geometry of diffraction and the path difference

As Figure 1 depicts, the incoming beam at an angle α to the grating's normal could be diffracted to a different outgoing angle β. In order to achieve a *constructive interference*, the "extra" distance that both wavefronts -the surfaces of *constant phases*- have actually traveled (shown in red and becoming equal to $d \sin\alpha + d \sin\beta$, where *d* is the *groove spacing*, also called the *pitch*), must correspond exactly to a multiple of the wavelength of the beam.

A sign convention is used to the angles of diffraction, making that diffracted beams lying on the same side of the normal that the incident beam are considered positive, while those outgoing in the other side are considered negative, as Figure 1 shows. The same convention applies for the orders of diffraction.

A special but common case is when the light is diffracted back toward the same direction from which it came ($\alpha = \beta$), called the *Littrow configuration*, which derives in a simpler spectrograph lay out.

In order to produce a sharp spectrum, besides the indispensable dispersing element the spectrograph requires additional optics: a *slit* for defining the input beam, a *lens for collimating* the beam onto the "spreader" heart, and a *lens for focusing* the diffracted beam onto the CCD detector.

The light through the telescope is focused onto the slit, and so it defines the size and shape of the incoming beam. The so selected portion of sky will be basically imaged at the CCD detector, so *the slit defines the resolution of the spectrograph* (the final imaged spectrum can be considered as a series of monochromatic images of the slit). A wider slit lets in more light but produces a large image and hence lower resolution.

A *fiber optic cable* can also replace the usual slit at the spectrograph's entrance by making that the fibers at this side became arranged in a line, that is, forming an *artificial slit* of fixed width equal to the diameter of the fibers.

The *collimating lens* produces a parallel beam of light which diameter must be matched to the size of the grating, thus achieving the best efficiency. The *focusing lens* has to focusing the resulting spectrum onto the CCD detector.

Fiber optics are normally used as the coupling element between the telescope and the spectrograph. Although there is an *intrinsic lost of light* inside the fiber link, it presents some advantages. The spectrograph has no longer to remain hung from the telescope (being able to be installed in a different temperature-controlled room), and also it is possible to obtain the spectra of several targets at the same time by accurately positioning the corresponding individual fibers, or even achieving simultaneously autotracking and spectra.

Spectrographs differ in their size and shape, but mostly in their *resolution*. The resolution of a spectrograph (R) is defined as the smallest increment which it can clearly resolve, and usually categorize spectrographs, as they are basically differenced as either of low (R<1,000), medium or high (R>10,000) resolution. Different resolutions are required for different studies and to suit the spread of brightness of the objects. The lower the resolution, the lesser the spread of the available light, thus allowing to study faint objects at the cost of only detecting their most notorious spectral lines. The higher the resolution, the opposite.

In spectroscopy, there is always a trade-off between spreading the scarce light resource as minimum as possible while obtaining enough resolution to see the desired features in a suitable short exposure. Different astronomical observations require different spectrographs, and this explains why there are so many different spectrographs in current use.

Modern professional spectrographs achieve resolutions greater than 50,000, being of large dimensions and maintained in stable environments. The currently highest resolution systems (R = 1,000,000) are very specialized, for example being used in the hunt for planets around other stars, as this search requires the highest precision in measuring radial stellar velocities.

The fundamental equations of a spectrograph

The Figure 2 is a general diagram of a grating spectrograph connected via a fiber optic cable to telescope, showing all the physical parameters and variables that rule its performance.

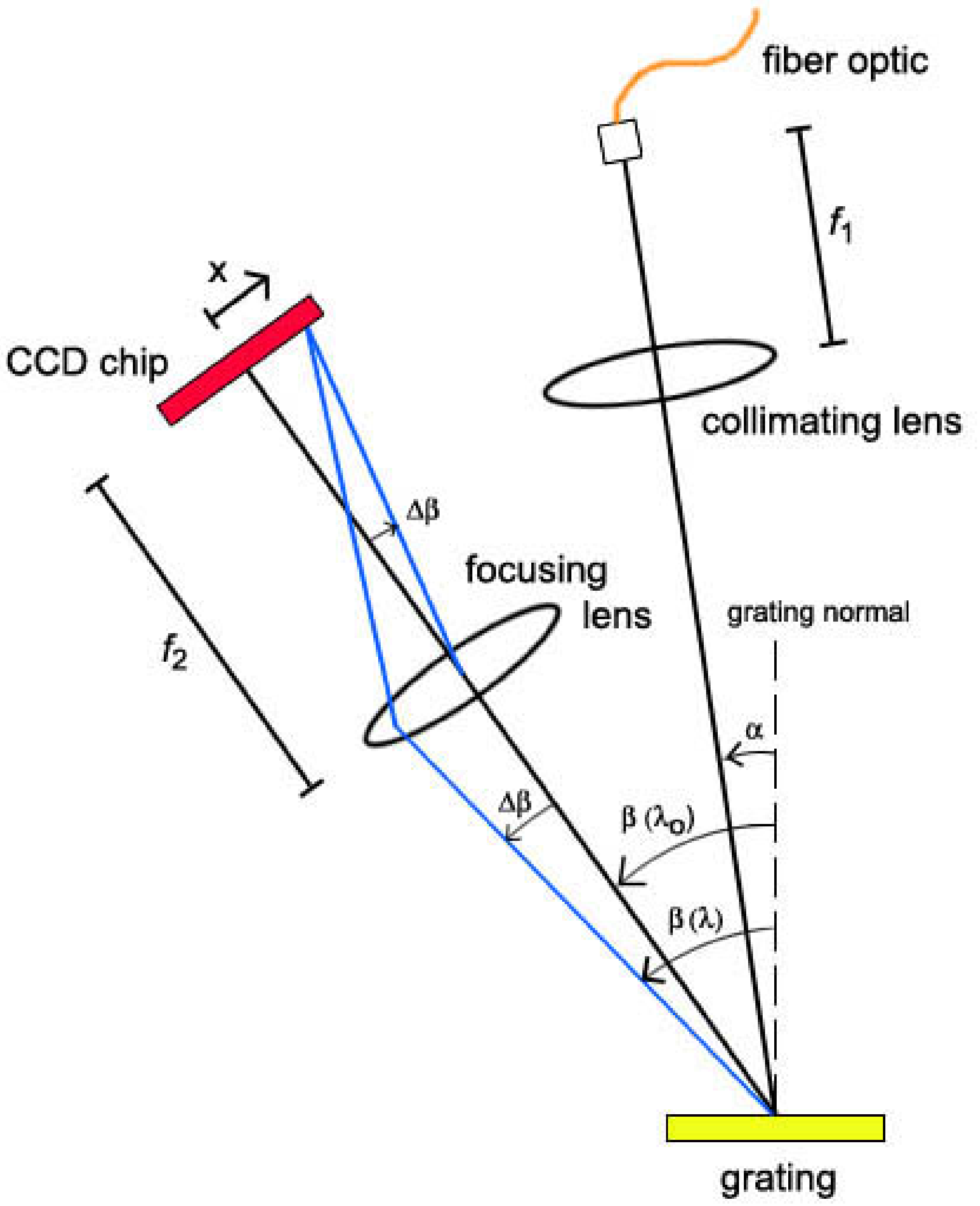


Figure 2
The elements of a reflective grating spectrograph coupled by an optical fiber

The definition of each parameter involved is:

f_1 = focal length of inlet collimating lens, expressed in mm
f_2 = focal length of exit focusing lens,
λ = wavelength of the monochromatic incident light
λ_0 = wavelength of the monochromatic incident light that makes that the diffracted light in the grating reaches the CCD detector (spectral image plane) exactly in its centre
α = angle of incidence of collimated light beam upon grating, measured counterclockwise from grating normal
β = angle of diffraction light beam from grating, measured counterclockwise from grating normal, that reaches the CCD detector in a variable lateral position
n = groove density of grating
N = total number of grooves on the grating
W_g = width of fully illuminated grating
R = ultimate theoretical grating resolution using the Rayleigh criterion
D_V = deviation angle between the incident light beam and the diffracted light beam
$D_V(\lambda_0)$ = deviation angle corresponding to the incident light beam and the diffracted light beam that reaches the CCD detector exactly in its centre
x = lateral position on the spectral image plane (CCD detector), measured from the centre of the image plane
w_1 = width of the entrance (as it is a fiber column, the diameter of a single fiber)
w_2 = width of the corresponding image of the entrance at the spectral image plane (CCD detector)
h_1 = height of the entrance (the total height of the fiber column)
h_2 = height of the corresponding image of the entrance slit at the spectral image plane (CCD detector)
k = integer diffraction order of the grating
Δx_p = width of a pixel on CCD detector
dx = differential lateral increment at the image plane
$d\lambda$ = differential wavelength increment
WR_{CCD} = wavelength range onto the CCD detector
N_p = total number of pixels at the CCD detector in the lateral (horizontal) direction

The grating equation

The most fundamental equation of the grating, from which all the following equations can be derived, is obtained by imposing a constructive interference to its phase difference (Figure 1), resulting

$$\sin\alpha + \sin\beta = k\, n\, \lambda \qquad (1)$$

where k is an integer (the *diffraction order* of the grating), and n the groove density (1/d). Both angles α and β actually depends on the wavelength λ that *makes the interference possible*.

The *grating equation* can be rewritten as

$$2\sin\left(\frac{\alpha+\beta}{2}\right)\cos\left(\frac{\alpha-\beta}{2}\right) = k\,n\,\lambda \tag{2}$$

Constant deviation monochromator

Assuming a *fixed position* for the input (fiber optic cable) and output (CCD detector) of the spectrograph, it operates as a *constant deviation monochromator*, that is, the angle between the input axis at the centre of the fiber optic cable, and the output axis at the centre of the CCD *do not vary at all*. Therefore, as shown in Figure 2, for any lateral position (*x*) on the image plane of the detector, there is an associated *deviation angle* as

$$D_V = \beta - \alpha \tag{3}$$

As $\beta = \beta\,(\lambda_0) + \Delta\beta$, the *deviation angle* becomes

$$D_V = D_V\,(\lambda_0) + \tan^{-1}\left(\frac{x}{f_2}\right) \tag{4}$$

It is important to realize that D_V is constant for a given *x*, that is, even making the grating rotate (which allows to change the wavelength λ_0 that occupies the central position at the CCD detector), both α and β actually vary, *but* D_V *remains constant*.

From (2) and (3) its comes out that

$$2\sin\left(\frac{\alpha+\beta}{2}\right)\cos\left(\frac{D_V}{2}\right) = k\,n\,\lambda \tag{5}$$

Solving the *grating equation* for α and β it becomes

$$\alpha = \sin^{-1}\left[\frac{kn\lambda}{2\cos\left(D_V/2\right)}\right] - \frac{D_V}{2} \tag{6}$$

$$\beta = D_V + \alpha \tag{7}$$

Therefore, supposing a *particular wavelength* λ is desired to fall at a *particular position x* on the CCD detector, first of all it must be calculated the *deviation angle* from (4), and then, by applying (6) and (7), the angles α and β can be found out. The incident angle α is a measure of the angle of orientation of the grating to produce the desired results, and *it is geometrically related to the positioning of the linear micrometer that makes the grating rotate.*

Dispersion

By differentiating the *grating equation* (1) with respect to the output angle β it is obtained the *angular dispersion*, becoming

$$\frac{d\lambda}{d\beta} = \frac{\cos\beta}{kn} \tag{8}$$

The *linear dispersion* is a measure of the lateral variation of wavelength across the spectral image plane -that is, at the CCD detector- usually expressed in units of wavelength per millimeter of lateral position increment (nm/mm). It can be obtained by differentiating the equation (8) with respect to the lateral position *x*, becoming

$$\frac{d\lambda}{dx} = \frac{d\lambda}{d\beta}\frac{d\beta}{dx} = \frac{\cos\beta}{kn}\frac{f_2}{f_2^{\,2} + x^2} \tag{9}$$

Therefore, the *linear dispersion* actually changes across the image plane (it explicitly depends on *x*, and also implicitly through the angle β), and this is why polynomial calibration curve fits are preferred when calibrating the spectrograph (thus is, finding the correspondence between the lateral position x and the wavelength λ). Whenever $f_2 >> x$ (the case of a small CCD chip), the dispersion is approximately inversely proportional to the focal length of the focusing lens.

A great $d\lambda/dx$ number actually means "a low dispersion", as any pixel at the CCD detector subtends a greater wavelength range (*wavelengths rapidly varying across the CCD*).

The total wavelength range imaged onto a CCD detector is approximately given by the *linear dispersion* value at the centre of the detector ($x = 0$) multiplied by the physical lateral width of the CCD chip, becoming

$$WR_{CCD} \approx \left(\frac{\cos\beta}{knf_2}\right) N_p \ \Delta x_p \tag{10}$$

Height and width of the spectral image at the CCD detector

The height of the image at the CCD detector (h_2) is the height of the vertical fiber column (h_1) multiplied by the ratio of the focal lengths of the focusing and collimating lenses, becoming

$$h_2 = h_1 \frac{f_2}{f_1} \tag{11}$$

The width of the image at the CCD detector (w_2) differs from the width of the diameter of the fibers (w_1) for two different transformation processes. One is due to an optical magnification factor (ratio of the different focal length lenses), and the other is due to the lateral magnifying effect of the ruled grating (the so-called *anamorphism* factor, as Figure 3 shows). This effect has a lateral magnifying effect on spectral lines, becoming

$$Anamorphism = \frac{\cos\alpha}{\cos\beta} \tag{12}$$

Thus, the width of the image at the CCD detector results wavelength dependent, as it depends on α and β, according to

$$w_2 = w_1 \frac{\cos\alpha}{\cos\beta} \frac{f_2}{f_1} \tag{13}$$

In order to obtain a smaller w_2, the width of the fiber column should be smaller, as well as the *anamorphism* factor and the focal lengths ratio.

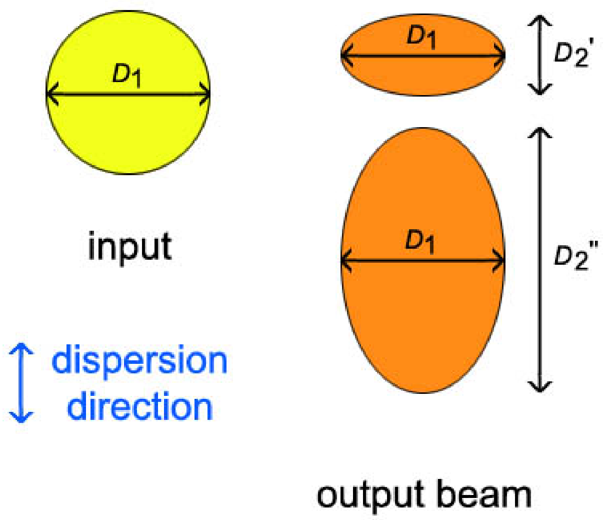


Figure 3
Anamorphism: at left, the beam as seen from the input towards the grating; at right, the diffracted beam as seen from the output towards the grating.

In Figure 3, the upper right shows the shape of the diffracted beam as seen from the output towards the grating, when the grating normal basically points towards the input (α angles being lower in value than β angles, and hence *anamorphism* becoming greater than 1). This *normal to collimator configuration* results in lower spectral resolution, smaller wavelength range, but larger oversampling. On the other hand, at lower right is depicted the shape of the diffracted beam as seen from the output towards the grating, when the grating normal basically points towards the output (α angles being greater in value than β angles, and hence *anamorphism* becoming lower than 1). This *normal to camera configuration* results in higher spectral resolution, larger wavelength range, but smaller oversampling.

Resolution

The diffraction limited resolution of a grating when fully illuminated with a collimated light beam (W_g exactly equals to the grating's height) derived from the Rayleigh criterion,

that is, the *theoretical maximum limit of resolution* of a given spectrograph design with a given grating size is

$$R = \frac{\lambda}{d\lambda} = k\,n\,W_g = k\,N \qquad (14)$$

This theoretical maximum limit of resolution value can rarely be achieved because of a variety of factors, in a very analogous case as the theoretical optical resolution of a telescope, just derived from the diameter of its primary mirror. In the case of the spectrograph, the factor limiting resolution is predominantly the finite entrance width w_1.

FWHM (or Instrument Bandpass)

The *FWHM* is a measure of how well a spectrograph system can resolve adjacent spectral lines, becoming something like a *"practical"* resolution (the lower *FWHM* value, the higher the *"practical"* resolution of the spectrograph). It is defined as the spectral width (usually expressed in nanometers) of an emission line from a monochromatic light source at half the signal height versus wavelength spectral plot. It is approximately given by the greatest size among a pixel (Δx_p) or the width of the image at the CCD detector (w_2), multiplied by the linear dispersion, that is

$$FWHM = \max\,(\Delta x_p, w_2)\,\frac{d\lambda}{dx}$$

For the usual case $w_2 > \Delta x_p$, from (9) and (13) it results

$$FWHM = \frac{w_1 \cos\alpha}{knf_1}\,\frac{f_2^{\,2}}{f_2^{\,2} + x^2} \qquad (15)$$

The *FWHM* is a function of wavelength because of its dependence on the angle α. For small x (small CCD chip) *FWHM* is approximately inversely proportional to both f_1 and n, so the spectrograph will increase its *"practical"* resolution by using a collimating lens of larger focal length and/or a grating with a higher groove density.

The design of an amateur grating spectrograph

The essential and first subject to define in the designing process of the amateur spectrograph is the selection of the element that is going to be used in order to disperse the light beam, and secondly, whether it would be optically coupled to the telescope in a direct (mechanical) way or by means of a fiber optic cable.

In this case, it has been chosen a *reflective grating* spectrograph linked by a *fiber optic cable*. The grating option was selected due to several factors (easy mounting and alignment, more technical literature available, better robustness), and the fiber optic option just by chance, as it was offered as a rejected piece from a spectrograph factory.

Having defined that the objective of this project was to construct a reflective grating spectrograph linked by fiber optics organized as a slit at the instrument's input, its lay out corresponds exactly to the diagram of Figure 2. Therefore, the design task basically consisted in the proper selection of the two required lenses (i.e., their respective diameters and focal lengths), and the minimum size and pitch of the grating, starting from the desired spectrograph's *theoretical resolution as the basic design parameter*. After the elements were selected, it ought to be checked that the spectrograph would properly work as a whole system, followed by the final design of the box and the exact location of each piece.

At a test bench many different elements and arrangements (different lenses, different angles, different orders, different locations and distances) were tried, as Figure 4 shows.

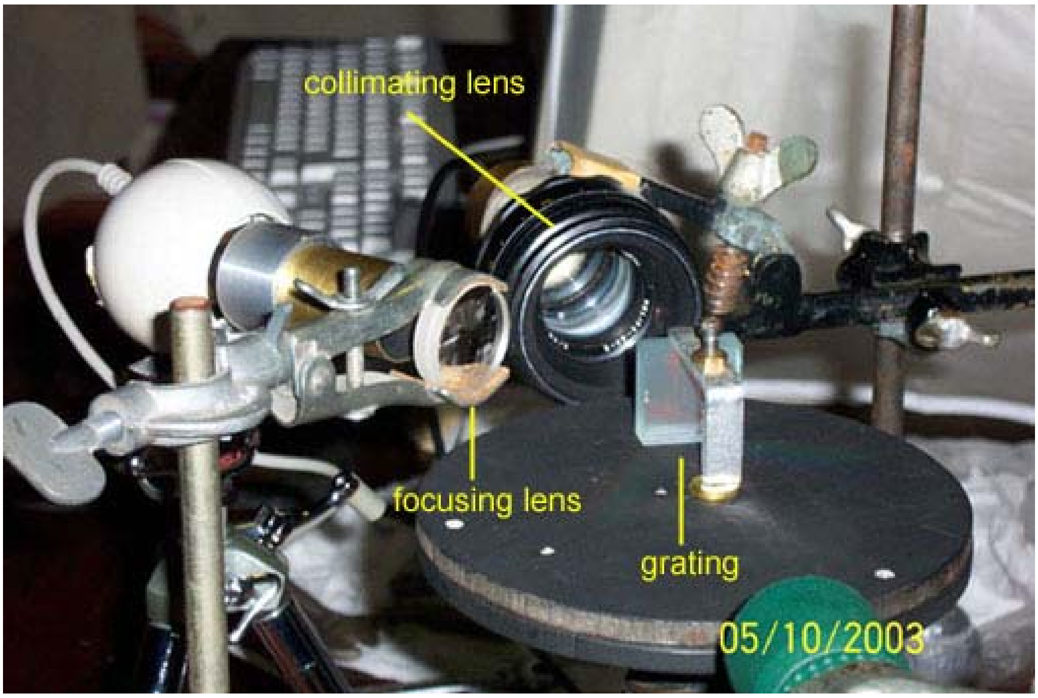


Figure 4
Several arrangements of the optical elements of the spectrograph were tested in the bench in order to evaluate each performance prior to the final design

The final selection of the spectrograph's elements and parameters were:

- The fiber optic cable (*fused-silica* core, *silica* cladding, 25 fibers of 50 μm) has a focal ratio FR_{fib} = 2.3 and provides good transmission from the UV through the IR. It has the fibers circularly organized in the usual way at the "telescope side", and arranged in a line at the "spectrograph side" to form an *artificial slit* at its entrance. Although it certainly has *some fibers misaligned* (easily observed in Figure 5, and explaining why it was given by free), it will work. The height of the fiber column at the entrance is about 1.3 mm.

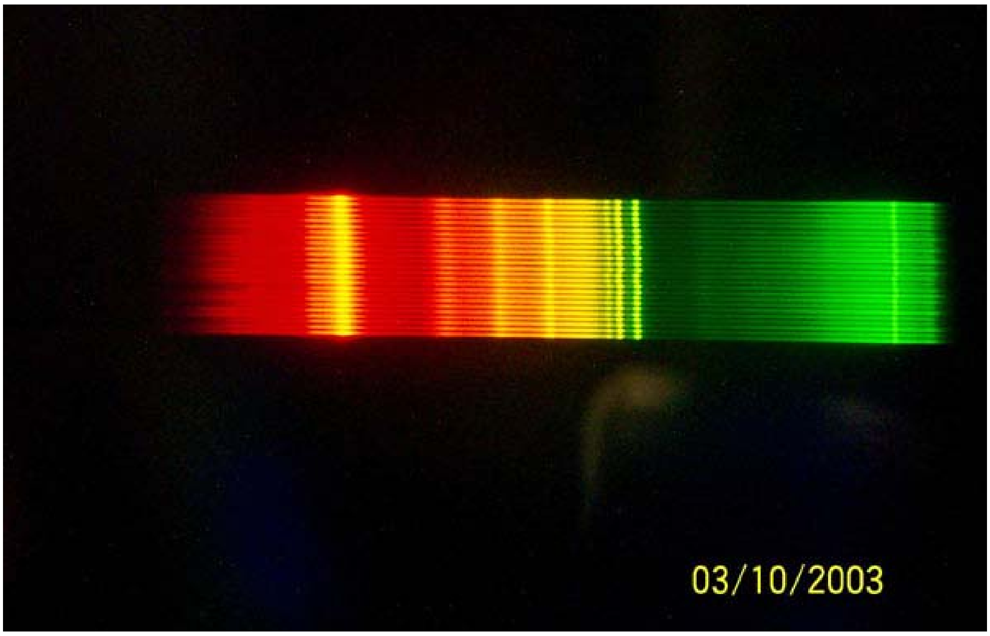


Figure 5
The spectrum of a mercury common lamp imaged with a comercial camera. The misalign of the fibers is evident. The bright yellow line on the red (at the left) do not correspond.

- The collimating lens is a used Russian camera *"Helios"* objective of diameter (D_{col})= 29 mm and focal length (f_1) = 58 mm (focal ratio FR_{col} = 2.0). It was obtained in the local second hand market.

- The reflective grating is a 1,200 grooves/mm, 30 x 30 mm, design wavelength = 500 nm, blaze angle = 17° 27'. It was ordered by mail to *Edmund Scientific* (ref # NT 46-077).

- The focusing lens is an achromatic brand new lens of diameter (D_{foc})= 30 mm and focal length (f_2) = 100 mm (focal ratio FR_{foc} = 3.3). It was ordered by mail to *Edmund Scientific* (ref # 32-499).

- The CCD camera is a *Meade Pictor* 216 XT, using a TI TC-255 CCD (size 3.30 x 2.40 mm, 336 x 242 pixels of 10 x 10 μm each), with good quantum efficiency between 4,000 to 8,600 angstroms.

- The *deviation angle* $D_V(\lambda_0)$ is chosen as 30° (a compromise between resting lower but at the same time assuring that the lenses do not become reciprocally overshadowed).

- The working *order for the grating* is chosen as +1, as it is its most intensive diffracted output (*the grating comes specifically marked with an arrow showing that sense*). Hence, the grating normal will be *"basically towards the collimating lens"*, as the value of the incident angle α will be always lesser than the value of the diffracted angle β. This configuration has an *anamorphism* factor greater than 1, and thus achieves a lower spectral resolution and smaller wavelength range, but a larger oversampling.

- The micrometer has a full length of 25 mm (Mitutoyo # 150-192). It was ordered by mail.

Having selected all the necessary materials and working parameters, the operational capability of the spectrograph has been established and hence can be calculated, as well as a check about the whole properness of the selected elements can be made. Those following calculations and verifications will assure an unobjectionable final design.

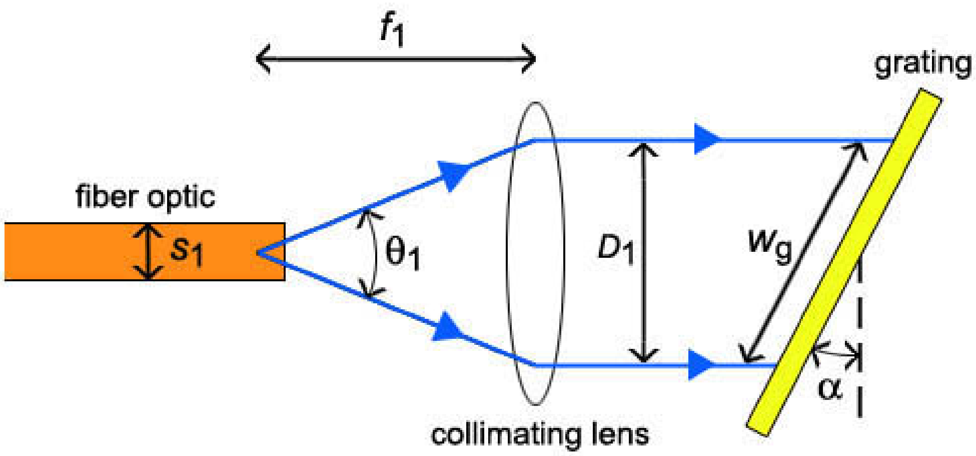


Figure 6
The input "side" of the spectrograph as seen from above

1) ***No vignetting at the collimating lens***

According to Figure 6, the collimating lens must be large enough than D_1 in order to not lose light from the telescope.

$$D_{col} > D_1 \Rightarrow FR_{col} < FR_{fib}$$

Since 2.0 < 2.3, this condition is fully satisfied.

2) ***The calculation of the diameter D_1***

From the Figure 6 it becomes that the diameter of the incident light beam on the grating is

$$D_1 = \frac{f_1}{FR_{fib}} = \frac{0.058}{2.3} = 0.0252 \text{ m} = 25.2 \text{ mm}$$

3) ***The calculation of the angles α and β***

From equations (6) and (7), assuming a particular wavelength of λ = 5,500 A, the incident and diffracted angles are

$$\alpha = \sin^{-1}\left[\frac{kn\lambda}{2\cos\left(D_V/2\right)}\right] - \frac{D_V}{2} = \sin^{-1}\left[\frac{1x1.2x10^6\, x5.5x10^{-7}}{2\cos\left(30/2\right)}\right] - \frac{30}{2} = 4.98\ °$$

$$\beta = D_V + \alpha = 30 + 4.98 = 34.98\ °$$

4) ***No vignetting at the grating***

From the Figure 6, the calculation of the minimum necessary grating size W_g for the particular wavelength of λ = 5,500 A, becomes

$$W_g = \frac{D_1}{\cos\alpha} = \frac{25.2}{\cos 4.98} = 25.3 \text{ mm}$$

As the grating's size to be used is 30 *x* 30 mm, this assures that no light will be lost.

5) ***No vignetting at the CCD detector***

From the Figure 7 it becomes that the diameter D_2 of the diffracted outgoing light beam from the grating at the particular wavelength of λ = 5,500 A is

$$D_2 = W_g \cos\beta = 25.3 \cos 34.98 = 20.72 \text{ mm}$$

D_2 results smaller than D_1, as expected from a *"normal to collimator"* configuration. For a total absence of vignetting at the CCD, the diameter of the focusing lens (D_{foc} = 30 mm) must be greater than D_2, which happens to be the case.

6) ***The calculation of the spectral dispersion on the CCD***

From equation (9), for the central position at the CCD detector (x = 0) and at the particular wavelength of λ = 5,500 A,

$$\frac{d\lambda}{dx} = \frac{\cos\beta}{knf_2} = \frac{\cos 34.98}{1x1.2x10^6 x0.1} = 6.83\ x\ 10^{-6} = 6.83 \text{ nm/mm}$$

For the normal CCD operation *("1x1 binning")* the width of a pixel (Δx_p) is 10 μm, so the *"normal" linear dispersion* becomes 0.683 A/pix, and for the *"2x2 binned"* CCD operation, the *"binned" linear dispersion* becomes twice the *"normal"*, that is, 1.37 A/pix.

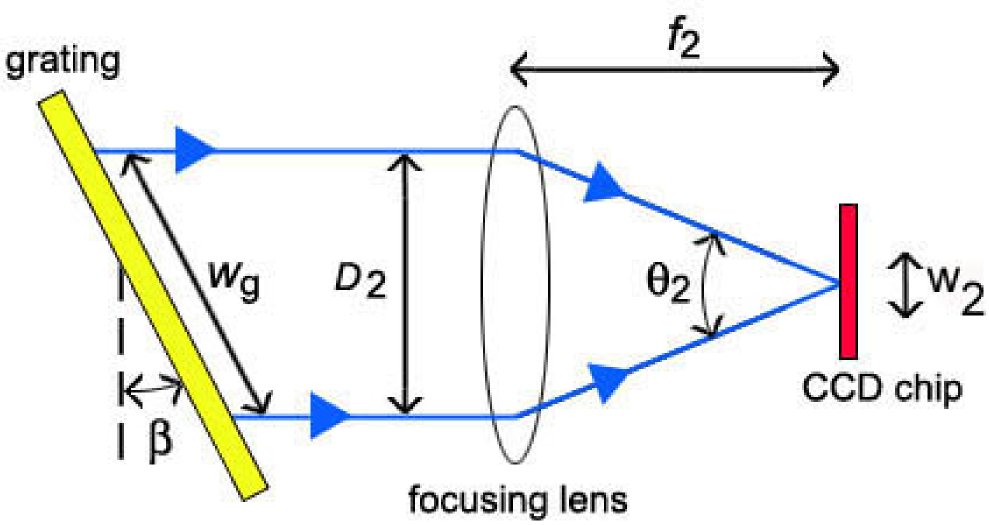


Figure 7
The output "side" of the spectrograph as seen from above

7) ***The calculation of the spectral wavelength covered range***

From equation (10) at the particular wavelength of λ = 5,500 A, the wavelength range at the CCD detector results

$$WR_{CCD} \approx \left(\frac{\cos\beta}{knf_2}\right) N_p\ \Delta x_p = \frac{\cos 34.98}{1x1.2x10^6 x0.1} 330\ x\ 10\ x\ 10^{-6} = 2.25x10^{-8} \text{ m} = 225 \text{ A}$$

8) ***The calculation of the height of the spectral image at the CCD detector***

From equation (11) at the particular wavelength of λ = 5,500 A, the theoretical height of the image at the CCD detector will be (assuming the height of the fiber column about 1.5 mm).

$$h_2 = h_1 \frac{f_2}{f_1} = 1.3\ x\ 10^{-3}\ x\ \frac{100}{58} = 2.24\ x\ 10^{-3} = 2.24 \text{ mm}$$

slightly smaller than the vertical size of the CCD chip.

9) ***The calculation of the anamorphism factor***

From equation (12) at the particular wavelength of λ = 5,500 A, the *anamorphism* factor results

$$anamorphism = \frac{\cos\alpha}{\cos\beta} = \frac{\cos 4.98}{\cos 34.98} = 1.22$$

10) ***The calculation of the width of the spectral image at the CCD detector***

From equation (13) at the particular wavelength of λ = 5,500 A, the theoretical width of the image at the CCD detector will be

$$w_2 = w_1 \frac{\cos\alpha}{\cos\beta} \frac{f_2}{f_1} = 50 \text{ x } 10^{-6} \text{ x } \frac{\cos 4.98}{\cos 34.98} \text{ x } \frac{100}{58} = 1.05 \text{ x } 10^{-4} = 0.105 \text{ mm}$$

that is, the width of the image will result the width at the entrance magnified slightly more than twice (as the fiber column is misaligned, the width w_1 is actually greater than 50 μm and hence w_2 will also be slightly greater than the obtained 0.105 mm).

11) ***The calculation of the spectrograph's theoretical resolution***

From equation (14) at the particular wavelength of λ = 5,500 A, the theoretical resolution of this instrument would be

$$R = k\ n\ W_g = 1\ x\ 1.2\ x\ 10^6\ x\ 0.0253 = 30{,}360$$

12) ***The calculation of the spectrograph's practical resolution***

From equation (15), for the central position at the CCD detector (x = 0) at the particular wavelength of λ = 5,500 A, the true capacity of this instrument for resolving adjacent lines becomes

$$FWHM = \frac{w_1 \cos\alpha}{knf_1} = \frac{50x10^{-6}\,x\cos 4.98}{1x1.2x10^6\,x0.058} = 7.16\ x\ 10^{-10} \text{ m} = 7.16 \text{ A}$$

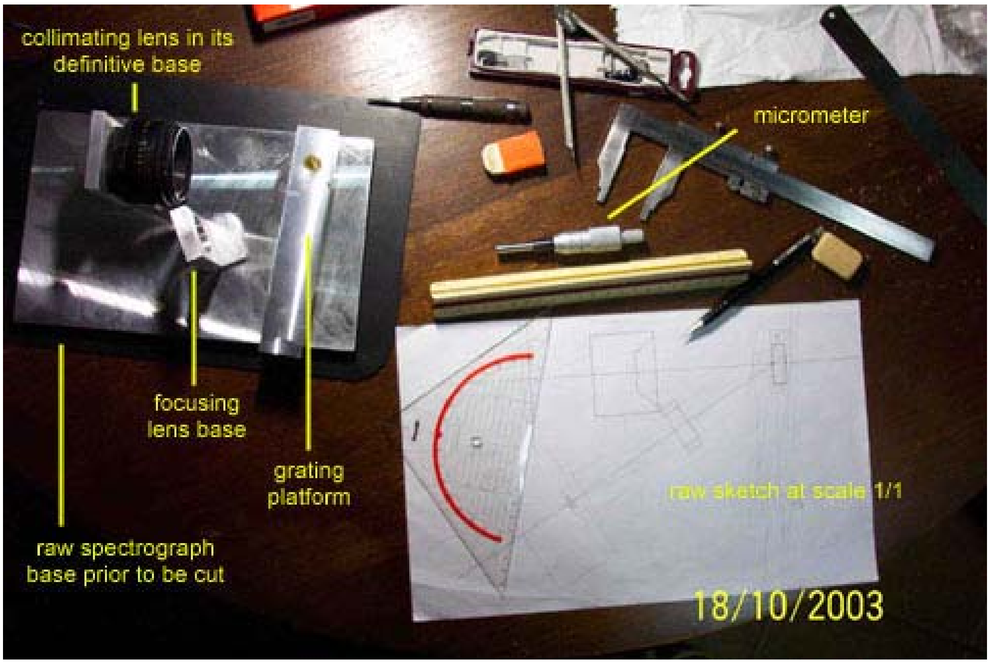


Figure 8
The final box design

13) ***The location of the micrometer***

Considering that the CCD camera has a good response from 4,000 A to 8,600 A, the corresponding incident α angles obtained from equation (6) for those wavelengths are

$$\alpha_{4,000} = -0.61° \qquad \alpha_{8,600} = 17.29°$$

Thus, the overall variation of the incident angle α will be about 18 °. Choosing an arbitrary angle of 84° with respect to the normal of the incident beam for the spectrograph's wall where the micrometer will be perpendicularly installed (just 6 ° less than the usual right angle) at a distance l_{mic} from the grating rotational centre, the total micrometer displacement (Δm) would be

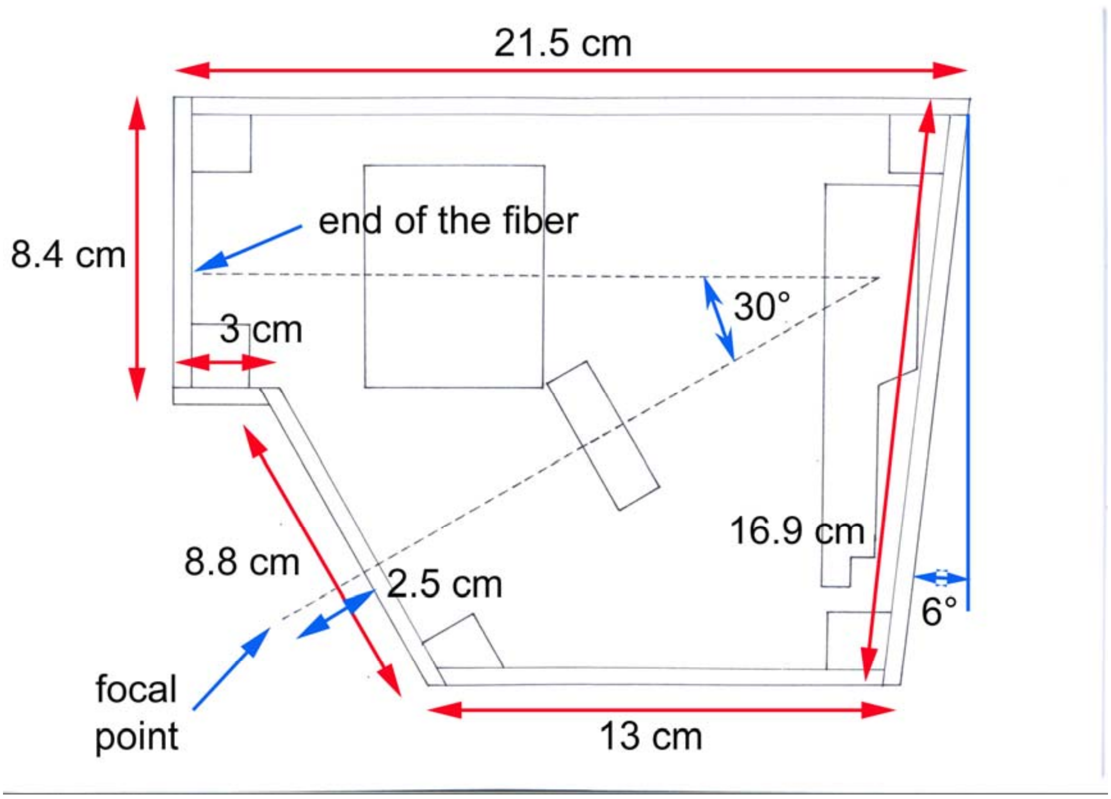
$$\Delta m = \left[\tan(17.29 - 6.0) + \tan(6.0 + 0.61)\right] l_{mic} = 0.31\, l_{mic}$$

Imposing that Δm = 25 mm, it results that l_{mic} must be 80 mm (a closer location would prevent to achieve the required angles for the extreme wavelengths, while a farther location would waste part of the 25-mm calibrated displacement of the micrometer).

14) ***The location of the collimating lens and the focusing lens***

The final decision about the spectrograph's lay out is the location of both lenses with respect to the grating (the distance from the fiber optic input to the collimating lens, as well as the distance from the focusing lens to the CCD detector output must perfectly coincide with their respective focal lengths). The lenses will be located as close to the grating as possible, but with some margin of error in order to absorb final adjustments without becoming overlapped.

Having conclusively checked that the spectrograph was well designed, the final blue print resulted in the following diagram:



The construction and alignment process of the spectrograph

The construction of the mounting pieces and the box, the mechanical assembly and the final adjustments in order to obtain a perfect alignment *were largely underestimated*, both in difficulty and time consuming.

Each mounting piece, as well as the box, was designed separately and ordered to be constructed in aluminum. It happened several times that the supposedly "finished" piece had to be rejected because it didn't achieve the required quality and precision standards.

All the aluminum pieces were painted in matt black to prevent stray reflections inside the box. For similar reasons, a matt black cardboard baffle was put between the entrance and the collimating lens, as shown in Figure 9.

After having the lenses stuck in their mountings, and the grating firmly placed onto its platform, all the pieces were assembled in the box. In order to facilitate the focal adjustment of the focusing lens, its mounting had been drilled with elongated holes. The collimating lens did not need this because it allows to vary its focal length by rotating an external focusing ring.

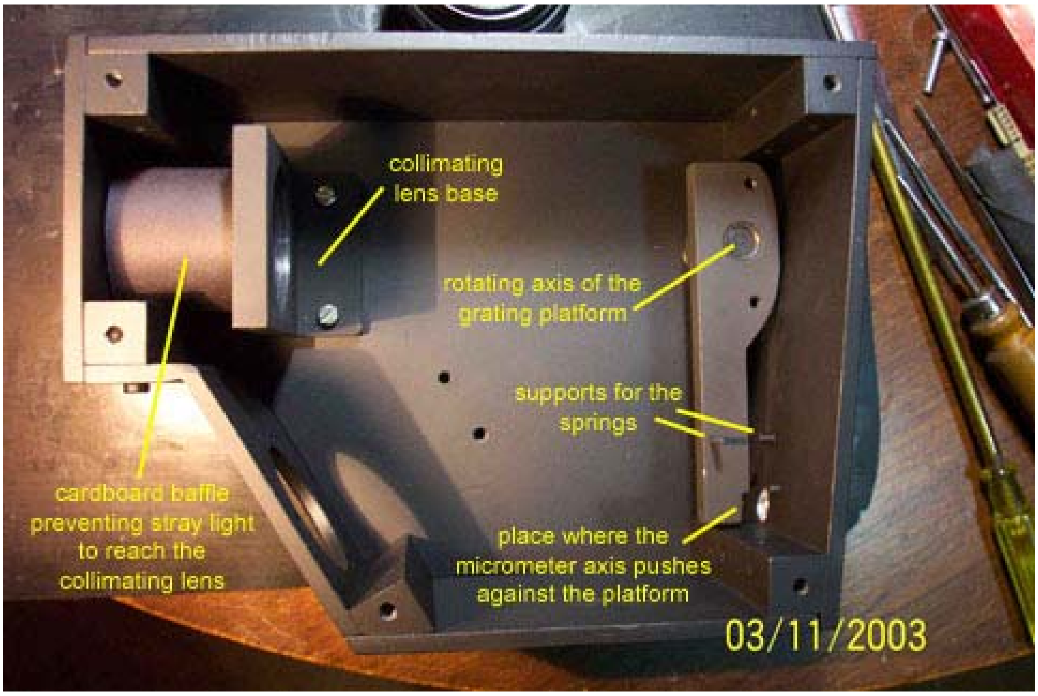


Figure 9
The finished box and the beginning of the assembly

The vertical alignment of the grating resulted critical. Only after three hours of trial and error, the grating was perfectly positioned by the final solution of placing a very fine paper under its base but only at the half front side. Figure 10 shows the correct alignment obtained for the desired diffraction order (k = +1), as well as the for k = 0 (reflection) and k = -1.

The final mechanical adjustments of the spectrograph implied the exact focal positioning of both lenses. As said before, the collimating lens is easier to adjust, so the focusing lens was firstly attempted. By slightly varying the location of the focusing lens while imaging at the CCD camera the spectrum of a common mercury lamp through the fiber cable, the best focal position was obtained and the focusing lens mounting became firmly and definitely screwed. Finally, a very fine turn of the focus ring of the collimating lens satisfactory ended the whole process of the spectrograph's construction and alignment.

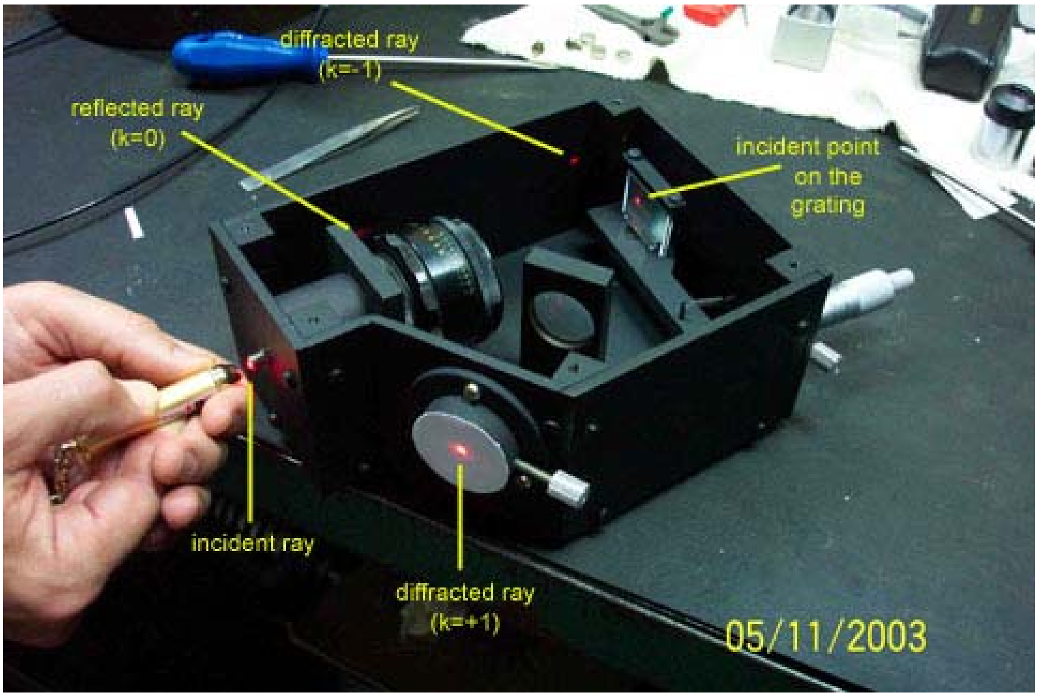


Figure 10
The final confirmation of the properness of the spectrograph's alignment.
It is interesting to also observe both the reflective and the diffracted ray or order – 1.

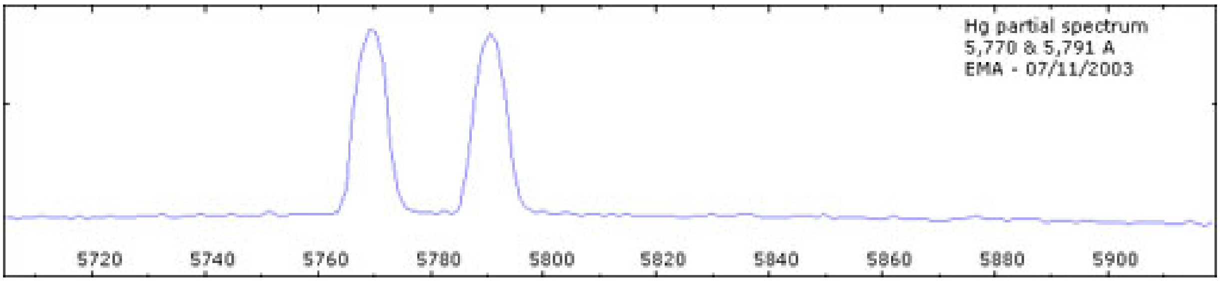
The assembled spectrograph weights about 2.5 kg, without including the CCD camera, and is about 22 *x* 16 *x* 9 cm without including the CCD camera and the micrometer.

The calibration stage

The first "real" test of the spectrograph was the capture of the full spectrum of a common mercury lamp (15 W, low consumption) through the fiber optic cable at work bench. It were obtained 51 images, each one for a 0.05 mm increment of the micrometer scale, from position 0.00 mm to position 25.00 mm.

The obtained image for the 12.50 mm micrometer position, were the twin spectral lines of wavelengths 5,770 and 5,791 A appear close to the centre of the image, was:

Applying it to the spectrographic analysis software *"Visual Specs"* available free over the Internet, and introducing the respective known wavelengths, it became possible to obtain the following referenced spectrum[4]:



The spectrum's wavelength range (from 5,703 to 5,921 A according to the software measure) corresponds to a span of 218 A, and the spectral dispersion results 1.353 A/pix. Those measured values are very similar to the previously corresponding calculated values at the planning stage (225 A and 1.37 A/pix) for a wavelength of λ = 5,500 A. The width of the emission lines at half their height comes out to be 7.2 A, in very good correspondence with the previous estimated *FWHM* value (7.16 A for λ = 5,500 A).

Replacing the CCD camera by a reticle eyepiece it was possible to measure the corresponding micrometer position that makes that each one of the spectral lines of the mercury lamp appears at the very centre of the image, whom exact wavelengths can be obtained from Internet.

Micrometer position (mm)	12.38	12.50	14.23	17.25	20.30	21.83	22.00
Wavelength (A)	5,791	5,770	5,461	4,916	4,358	4,078	4,047

4 The *"Visual Specs"* program assumes a linear relationship between wavelength and pixel position, which is valid only to a first approximation. A precise calibration implies the assumption of a third-order polynomial relationship, so that at least four pairs of the wavelength-pixel position curve must be known in order to find out the four coefficients that define its mathematical expression.

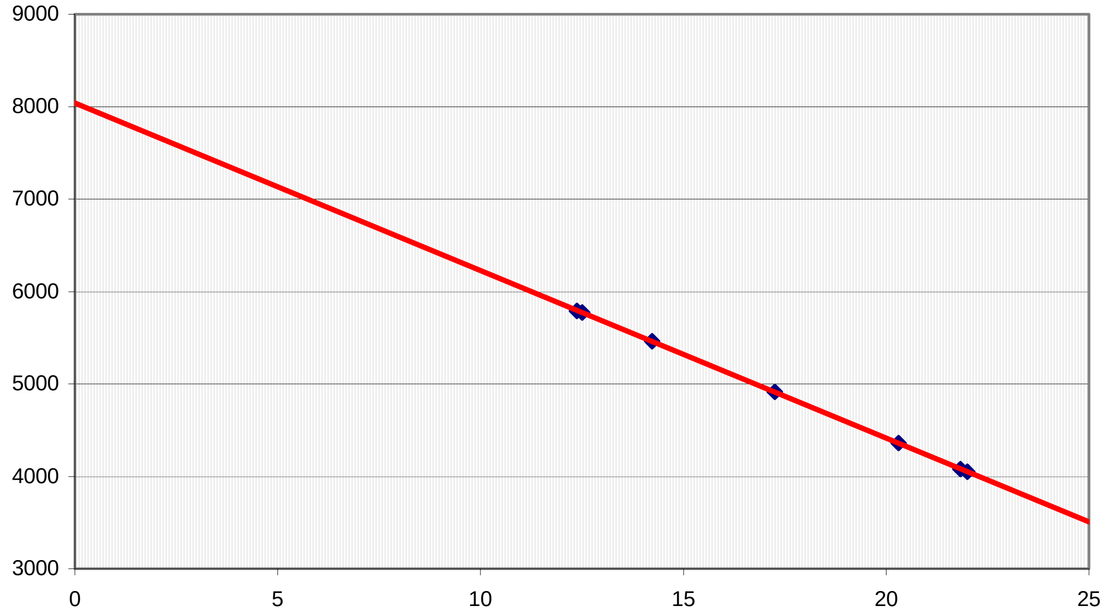


Figure 11
Relationship between the micrometer position (in millimetres) and the resulting central wavelength (in angstroms), obtained at bench from a mercury lamp

Plotting the respective obtained values, as shown in Figure 11, it results that there is a quite linear relationship between the micrometer position and the central wavelength of the corresponding spectrum, at least for the measured interval (from 4,047 to 5,791 A). The mathematical expression for this linear relationship becomes

$$\lambda = - 181.32\ MP + 8036.1 \qquad (16)$$

where *MP* (in millimeters) is the micrometer position that makes that the wavelength at the exact centre of the spectrum becomes λ (in angstroms).

Assuming that the linear relationship is valid (*at least as a first approximation*) for the full displacement range of the micrometer, the red line has been extrapolated from 0 to 25 mm.

The span of the overall wavelength range (4,500 A) coincides pretty well with the desired size of 4,600 A, although its appears displaced (3,550 to 8,050 A instead of 4,000 to 8,600A). This can be easily corrected by slightly rotating the grating or supplementing the place where the micrometer push against the platform.

This repositioning, as well as the *flux calibration* of the overall system has not yet been made at the time of writing this report.

The spectrograph at field

The use of the spectrograph at field, that is, the capture of spectral CCD images through the telescope, implied *several tasks that had to be properly performed in advance.*

First of all, the "telescope side" of the fiber optic cable (mounted at the centre of a standard eyepiece holder) had to be placed at the telescope's right focal position, that is, *the telescope needed to be exactly focused on the fiber cable* (while this is not such a very difficult task for a given fixed target -just trial and error- the big problem arises when a "moving" target has to be centred).

The bundle of fibers to be attached to the telescope has a diameter of about 300 μm, which means a sky covering of only about 30 arcseconds for the used 20-cm Schmidt-Cassegrain telescope (*Meade*'s LX-90) working at f/10. This very modest field makes very difficult the proper aiming to any desired target. It became absolutely necessary to use a *flip mirror system* (*Meade*'s model 644) with an illuminated reticle eyepiece in order to facilitate the pointing.

The usefulness of a flip mirror system (Figure 12) lays in two prior works. Being the field so tiny, in order that the stellar target at the centre of the reticle appears exactly at the centre of the fiber cable, the flip mirror system *has to be exactly aligned*. On the other hand, the reticle eyepiece has to be in focus for the very same position where the fiber cable becomes focused. Assuring this two topics, *the use of a flip mirror system becomes indispensable.*

Figure 12
The flip mirror, the reticle eyepiece and the fiber optic cable

As the fiber optic cable, the micrometer and the CCD camera (the three detachable pieces of the spectrograph) *have to be always remounted at the observational place*, the last task was to confirm that all of them have been properly positioned, that is, the column fiber at the entrance standing *perfectly vertical*, the graduated scale of the micrometer laying in its *right position*, and the large axis of the CCD chip becoming *perfectly horizontal*.

Having checked all the aforementioned subjects, the alignment of the telescope done, and the CCD camera reached its stabilized operating temperature, each spectral imaging sessions properly could begin. Only spectra of stars of first magnitude were imaging. The exposure was firstly adjusted at 60 seconds, but then changed to 30 seconds, as the captured information seemed to be quite the same . In the same line of reasoning, the CCD camera was used in the *"2x2 binning"* option, which implied a *great saving in the camera processing times*.

The telescope's alt-azimuth mounting (shown in Figure 13) did represent a *serious drawback* for the capture of the spectral images. The otherwise tolerable drifting in the case of direct observation, *turned to be excessive for this application, becoming a mayor annoyance*. It implied that a lot of images had to be retaken, and the accurate aiming of the target necessarily had to be reconfirmed at the very centre of the reticle after every single spectral shot, as most of the times the telescope had slightly drifted and it needed to be repositioned for the same target. A proper tracking system based on an equatorial mount would have prevented those difficulties, but it was out of reach.

Having "learnt" about the intrinsic difficulties of stellar spectral imaging with the available equipment (telescope and mounting), four field sessions were actually performed between November 9 and 16, 2003, in search for stellar spectral imaging (Figure 13).

Figure 13
The telescope and the spectrograph system at field

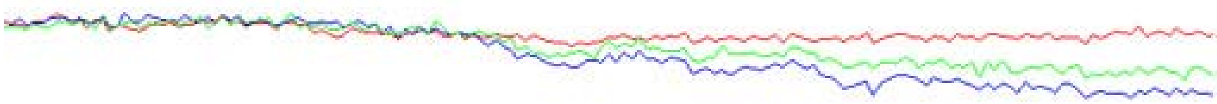
Analysis of the obtained spectra

All the spectral images were taken with the CCD at minus 5° C, 30 seconds exposure. They were only processed by subtracting the corresponding *dark frame*. The flux has not been calibrated, meaning that the level (the vertical displacements) for each spectrum is different. Therefore, the only valid information deducted from their comparison is the presence or absence of particular spectral lines at the considered wavelength range.

Following are the obtained spectra for the micrometer position at 8.50 mm, corresponding to Canopus (green), Sirius (blue), Aldebaran (purple), and Betelgeuse (red).

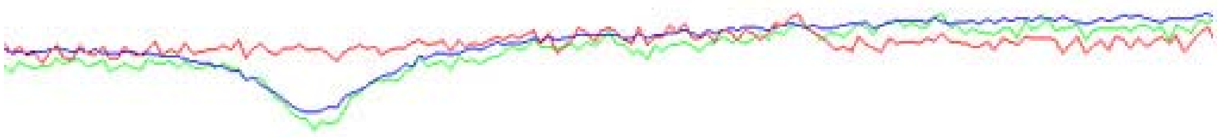
According to equation (16) the central wavelength should correspond to 6,495 A, and the full range would be 6,385 to 6,605 A. Therefore, the clearly visible absorption line shown in the blue and green spectra is the Hα line (6,563 A), although it appears more displaced towards the left of the expected position (this could be due to the 15 ° C difference in temperature between the spectrograph's temperature at the moment of its indoors calibration and the outdoors temperature at the times of the field imagining). Neither the purple, nor the red spectra present any notorious line.

Following are the obtained spectra for the micrometer position at 12.00 mm, corresponding to Canopus (green), Sirius (blue), and Betelgeuse (red).



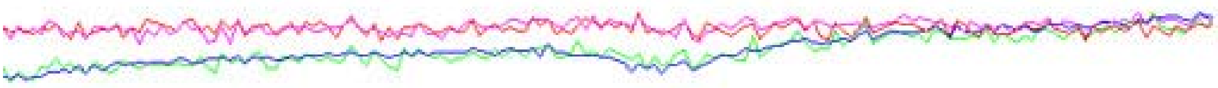
According to equation (16) the central wavelength should correspond to 5,860 A, and the full range would be 5,750 to 5,970 A (this range was selected due to the Na I line at 5,890 A). No one of the shown spectra happen to have any notorious line in this wavelength range. Both the green and blue spectra seem to present a slight monotonous declination towards the right (as the wavelength increases).

Following are the obtained spectra for the micrometer position at 17.50 mm, corresponding to Canopus (green), Sirius (blue), and Betelgeuse (red).



According to equation (16) the central wavelength should correspond to 4,863 A, and the full range would be 4,753 to 4,973 A. Both the green and blue spectra show a prominent absorption line, that corresponds to the Hβ line (4,861 A), and in the same way like the previous case, it appears more displaced towards the left of the expected position.

Following are the obtained spectra for the micrometer position at 22.00 mm, corresponding to Canopus (green), Sirius (blue), Aldebaran (purple) and Betelgeuse (red)



According to equation (16) the central wavelength should correspond to 4,047 A, and the full range would be 3,937 to 4,157 A (this range was selected due to the Ca II line at 3,968 A). The slightly apparent absorption line that appears in both the green and blue spectra corresponds to the Hδ line (4,102 A), and in the same way like the previous cases, it appears more displaced towards the left of the expected position. Conversely to both the yellow and red spectra, both green and blue spectra seem to have a slight tendency to decrease towards the left (decreasing with the wavelength). Neither the purple, nor the red spectra present any notorious line.

From the overall analysis of the obtained spectra it comes out that the "green" and "blue" stars must be of spectral class A or F, as those are the stars that show the most prominent *Balmer* lines of hydrogen (Hα, Hβ, Hγ, and Hδ). On the other hand, the "purple" and the "red" stars show very similar spectra at the narrow considered wavelength ranges, so their spectral class should be about the same or at least "contiguous" and quite "distant" from class A or F.

Comparison to published data

Observing the spectral examples for each spectral class[5], it results that around 5,900 A, classes O to F present a steady decreasing towards higher wavelengths, which doesn't show up in class M. In a similar way, around 4,000 A spectral classes A and F decays towards lower wavelengths, while class M remains basically constant. This supports the initial conclusions about the spectral classes of the imaged stars.

Therefore, the four analyzed stars can be divided into two groups of similar spectral characteristics:

- Sirius and Canopus, showing *similar stronger hydrogen absorption lines, belonging to the same spectral class or adjacent*, probably classes A or F.

- Aldebaran and Betelgeuse, showing *no visible hydrogen absorption lines, belonging to the same spectral class or adjacent*, probably classes K or M.

A comparison of the real flux values of each spectrum would have provided the required information in order to elucidate their respective spectral classes, but, as said before, the system's *flux calibration* has not yet been done.

From the published data[6] becomes the final confirmation:

	Sirius	Canopus	Aldebaran	Betelgeuse
Spectral class	A1 V	A9 Ib	K5 III	M2 Iab
Magnitude	- 1.44	- 0.62	0.87	0.45

Spectrograph specifications

The verified characteristics of the constructed spectrograph are summarized as follows:

Type	**Constant Deviation Monochromator (30°)**
Coupling	**Fiber optic cable of 25 fibers, each 50 microns in diameter**
Micrometer range	**0 to 25 mm, graduated at 0.01 mm**
Grating	**1,200 grooves per mm, 30 x 30 mm, used at order + 1**
Anamorphism	**1.22**
Resolution (theoretical)	**30,360**
Resolution (FWHM)	**7.2 angstroms at the central wavelength**
Spectral range	**4,500 angstroms (from about 4,000 to 8,500)**
Dispersion	**6.83 nm/mm at the central wavelength**
Wide of a single spectrum	**225 angstroms approx for the used CCD (*Meade's 216 XT*)**

[5] "*Practical Amateur Spectroscopy*" by *Stephen F. Tonkin*, pages 43-49.
[6] "*Observer's Handbook 2003*" by The Royal Astronomical Society of Canada, pages 242-250.

Conclusion

Although very simple in its conceptual design, the constructed spectrograph does have a useful scientific potentiality. Its fine resolution makes it possible to undertake several interesting studies within reach of a common amateur 20-cm telescope, like supernova identification or even galaxy redshifts. However, it must be emphasized that a proper tracking system becomes an absolute necessity.

The considerable time investment that the construction of this spectrograph actually demanded has been worth while, as the instrument has fulfilled the original expectations. However, the accomplished endeavour has been *just a first step*. There is a lot of work ahead. It is necessary to achieve mastering in the practical use of the *telescope-spectrograph-CCD* system and find out its limitations. The related software tools, like the *Visual Specs* program, must be deeply known and fluently handled.

Only after achieving such proficiency the constructed spectrograph will certainly allow the acquisition of the scientific information that has been the main objective at the time of choosing this project, objective that now may materialize soon.

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Also, the author desires to underline the generous and uninterested gift of a fiber optic cable received from Dr. Joseph Sivo, despite no personal or commercial relation exists between them. The author had emailed him just to ask for some advices, and ended up with a free cable that certainly made it possible to construct a more interesting spectrograph with a wider range of potentiality.