

Spectrographs

A spectrograph is an instrument used to separate and measure the wavelengths present in Electromagnetic radiation and to measure the relative amounts of radiation at each wavelength. In other words obtain and record the spectral content of light or its 'spectrum'. The spectrograph splits or disperses the light from an object into its component wavelengths so that it can be recorded then analysed.

Light entering a spectrograph can be split or dispersed into a spectrum by one of two means, using a prism or a diffraction grating. When Newton split light into a spectrum in the 1660s he used a glass prism in a similar manner show in the diagram below.

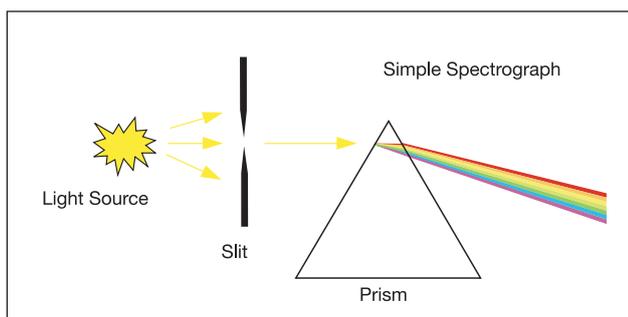


Figure 45 - Spectrum

This effect arises due to the fact that the different wavelengths of light also have different wavelengths or energies. As they pass through a prism, they undergo refraction, a change in velocity due to the change in medium. If the light falls incident to the prism at an angle other than 90° it will also change direction. Blue light has a shorter wavelength than red light so its angle of refraction is higher, both at entry to and exit from the prism. This means it gets bent more. The effect is the same effect which generates a rainbow in a rain shower, with the droplets of rain acting as prism to disperse or split the light into its component colors.

Diffraction Gratings

A diffraction grating is an optical element, which separates (disperses) polychromatic light into its constituent wavelengths (colors). The polychromatic light incident on the grating is dispersed so that each wavelength is reflected from the grating at a slightly different angle. The dispersion arises from the wavefront division and interference of the incident radiation from the periodic structure of the grating. The dispersed light is then re-imaged by the spectrograph and the required wavelength range is directed to a detection system. Gratings consist of equally spaced parallel grooves, formed on a reflective coating and deposited on a substrate. The dispersion

and efficiency of a grating are dependent on the distance between adjacent grooves and the groove angle. Gratings are generally better than prisms, they are more efficient, they provide a linear dispersion of wavelengths and do not suffer from the absorption effects that prisms have which limits their useful wavelength range.

The grating equation

The dispersion of a grating is governed by the grating equation, usually written as:

$$n \cdot \lambda = d \cdot (\sin \theta_i + \sin \theta_d)$$

where: n is the order of diffraction, λ is the diffracted wavelength, d is the grating constant (the distance between successive grooves) θ_i is the angle of incidence measured from the normal and θ_d is the angle of diffraction measured from the normal. The diagram below shows the orders of the diffracted wavelength. As well as positive orders, light can also be diffracted in the opposite direction (i.e. $n = -1, -2$ etc.). Higher orders may also appear but these decrease in intensity. Usually the first order lines ($n=1$ or $n=-1$) are the most intense. See Figure 46 below.

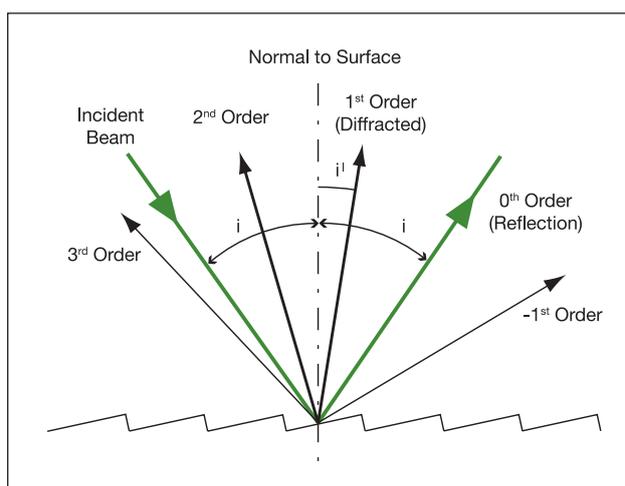


Figure 46 - Diffracted Orders

Grating orders & blazing

Gratings can be designed to concentrate most of the incident intensity into a particular order, by a process called “blazing”. This is a process where the grooves of a grating are cut so that the reflecting surfaces are at a certain angle, the blaze angle. About 90% of the incident light is diffracted preferentially into the first order. Blazing works best when the incident beam and the diffracted beam fall equally on either side of the blaze angle.

When incident light is dispersed by a grating, more than one spectrum may be formed. These spectra or ‘orders’ can overlap. Examination of the grating equation shows that the diffracted angle of a wavelength of light λ_1 in the 1st order will be the same angle or direction for the wavelength λ_2 in the second order where $\lambda_2 = \lambda_1/2$. These higher orders could cause confusion when measuring a spectrum of light. In this case, order sorting filters should be used to block the second order light and thereby reduce errors in the measurement of the spectra.

The Free Spectral Range

Simply stated, the free spectral range of a spectrometer is the wavelength interval, $\partial\lambda$, for which there is a single-valued relationship between wavelength λ and the position $x(\lambda)$ of the entrance slit image. For prisms, the free spectral range usually covers the whole region of dispersion of the prism (and is determined by the nature of the material used) whilst for grating spectrometers the free spectral range is determined by the grating diffraction order n . So for grating spectrometers, the free spectral range is the range of wavelengths in which there is no interference or superposition of light from adjacent orders.

Using the grating equation we can show for light incident vertically ($\theta_i = 90^\circ$) and wavelength λ will be diffracted at an angle θ_d so that $\lambda_1 = d \sin \theta_d$. A second wavelength λ_2 in a higher order ($n+1$) will also be diffracted in the same direction angle if $(n+1)\lambda_2 = d \sin \theta_d$, Hence the free spectral range, therefore, can be expressed as

$$\partial \lambda = d \sin \theta_d \left[\frac{1}{n} - \frac{1}{n+1} \right] = \frac{d \sin \theta_d}{n(n+1)}$$

Thus the free spectral range decreases with increasing diffraction order, and applies to all gratings capable of operating in more than one order. It becomes an important factor with specialized gratings, such as Echelle gratings, that function at very high orders, as well as with many interferometers. All these devices exhibit very limited (small) free spectral ranges.

Czerny-Turner Spectrograph

There are many arrangements of spectrographs using plane gratings but a representative one is the Czerny-Turner spectrograph shown below.

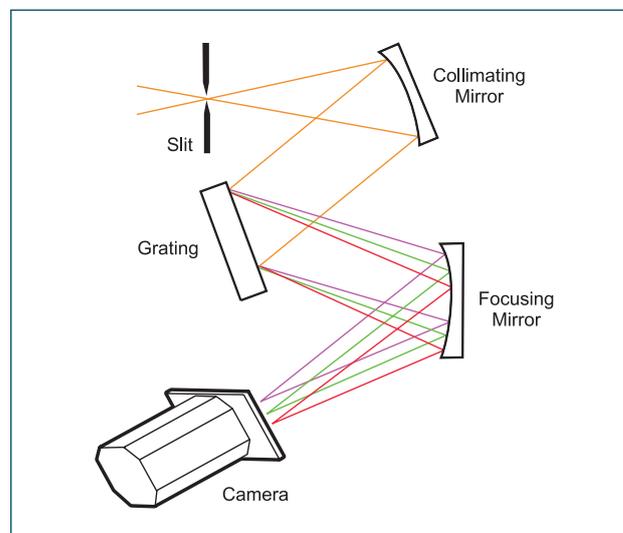


Figure 47 - Illustration of grating orders and blazing

A spectrograph typically contains two types of optics. The first forms an image of the source, the second disperses the light or makes an angular deflection of the light as a function of the wavelength. Together they make an instrument which forms multiple images of the source, one for each of the separate resolved wavelengths.

In the Czerny-Turner spectrograph the imaging optics use a pair of concave mirrors and the dispersive element is a plane grating. The first mirror collimates the light from the slit and directs it on the grating. The second mirror gathers the light from the grating and directs the multiple images of the input slit onto the detector. The concave mirrors are carefully arranged to minimize the optical aberrations introduced by the mirrors. The range of wavelengths detected can be varied by rotating the plane grating angle to select the required diffracted images.

The off angle mirrors do introduce an astigmatism aberration which takes an image of a point and stretches it into a line. For regular spectroscopy this is not usually a problem however if the experimenter is imaging multiple fibres or is imaging a line the astigmatism can degrade the effective spatial resolution or cause multiple spectra from individual fibres to overlap. In this case an imaging spectrograph needs to be used.

An imaging spectrograph removes the astigmatism in one of two ways. The spectrograph can either use specially designed mirrors called toroidal mirrors to correct the astigmatism or use correction optics. Toroidal mirrors have different focal lengths

for the vertical and horizontal direction and correct the use of the mirrors off axis. Toroidal Mirrors are used in the Shamrock 303 spectrograph. An alternative method is to use a correction optic in the spectrograph and Andor uses a patented optic in the Shamrock 163i to achieve good imaging resolution.

Echelle Spectrograph

The use of plane gratings for high resolution spectrographs was started with the introduction of the Echelle spectrograph in the 1940's. Prior to this concave grating were used in the 2nd or sometimes the 3rd order to obtain a high dispersion spectrograph. The Echelle spectrograph uses a plane grating at high angles of incidence and diffraction or essentially at very high orders to take advantage of the consequent high resolution and dispersion. An Echelle spectrograph uses a grating with a large spacing and as the grating is used over a smaller range of angles it can be blazed with a well shaped groove to be more efficient throughout a very wide range of wavelengths.

To individually resolve all the wavelengths the Echelle spectrograph must use a second dispersion element of lower dispersion to be able to resolve the different free spectral ranges.

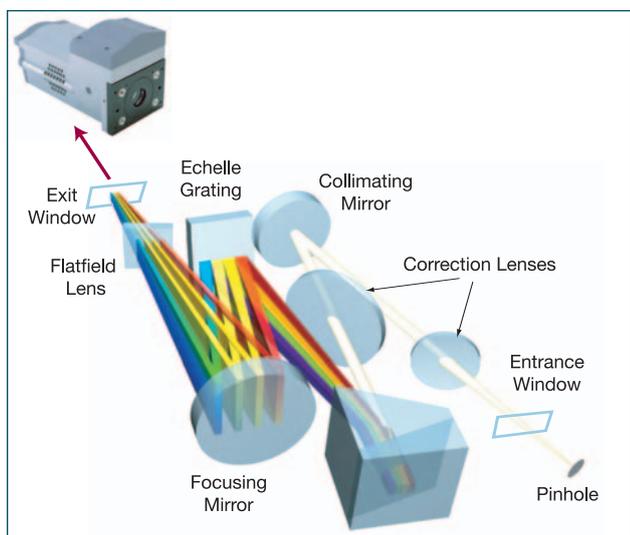


Figure 48 - Echelle spectrograph

In the Andor Mechelle spectrograph the second dispersion element is a patented compound prism as shown in Figure 48 below.

The Light from the entrance pinhole is collected and collimated by patented optics to ensure high efficiency collection and low crosstalk among the orders. The light is passes twice through a

patented compound prism to provide vertical dispersion of the wavelengths of the free spectral ranges. The light then falls onto an Echelle grating which creates the high dispersion in the horizontal direction of the spectra necessary to achieve the appropriate resolution, The echellegram is then relayed by the focussing mirrors onto the imaging detector.

The patented compound prism allows the orders to be optimized for maximum wavelength coverage with the lowest cross talk. If you compare an echellegram using a simple prism you can see the low dispersion of the prism in the near

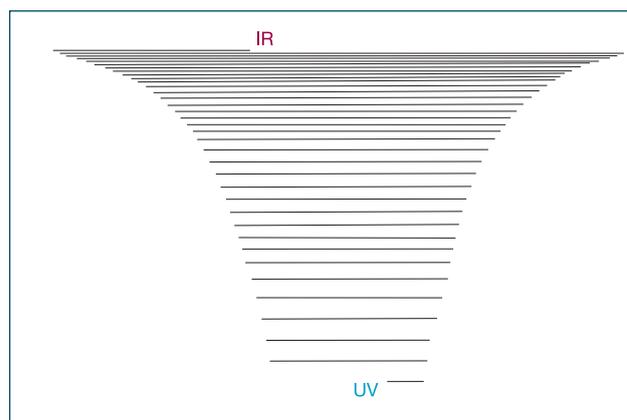


Figure 49 - Echellegram using standard prism

infrared causes the orders to bunch up and overlap while the high dispersion of the prism in the UV causes the orders to be spread out very far.

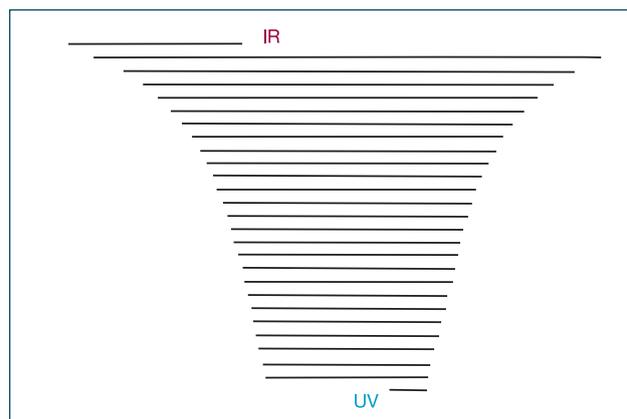


Figure 50 - Echellegram using Andor patented prism

Using the Andor patented compound prism the dispersion differences in different materials can be exploited to provide linear dispersion over the entire wavelength range and thereby achieve a much more efficient use of the detector camera.