Technical Note

Echelle Optics Explained Simply

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A question often asked is "What is an echelle spectrometer? Why are they used?" Originally invented for astronomy, echelle optics were first used in atomic spectroscopy on the DCP (direct current plasma) and more recently in ICP (inductively coupled plasma). It is a very compact optical design of less than 0.4 meters long, incorporating usually a course grating e.g. 120 g/mm and a prism as a cross disperser. Instead of having a linear spectrum, with intensity of line against wavelength, the echelle, using a cross disperser, creates a two dimensional spectrum with wavelengths across and in a series of lines going down, like the text in a page of a book. Figure 1 shows a typical echelle spectrum.

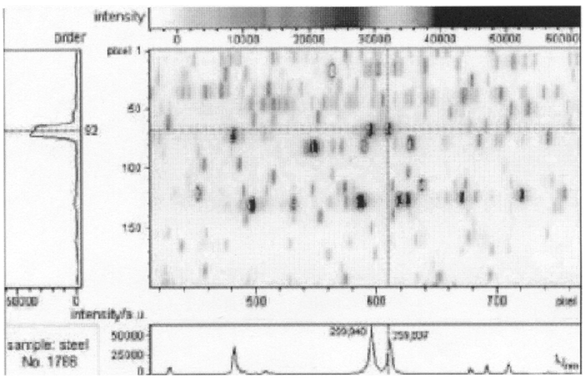

Figure 1: Echelle two dimensional spectrum

There are many designs of echelle optics, most use prisms, (some designs use a grating as the cross disperser), the basic format however, is similar. The course grating creates low resolution, then the cross disperser creates enhanced resolution two dimensionally. The coarse grating and the prism utilize multiple orders, typically between 50-120, to cover the normal spectral range required for ICP.

This optical design is ideal for simultaneous solid state detector (SSD) ICP spectrometers due to the shape and size of the chip. The shape of the spectrum is an off-axis bell shape (Figure 2), however, about 30% of the chip area is not used. There are also limitations on the wavelengths available, due to the focusing optics, the chip size, the number of pixels per chip, and the desire to use as much of the chip area as possible, with minimum loss of wavelengths falling off the edge.

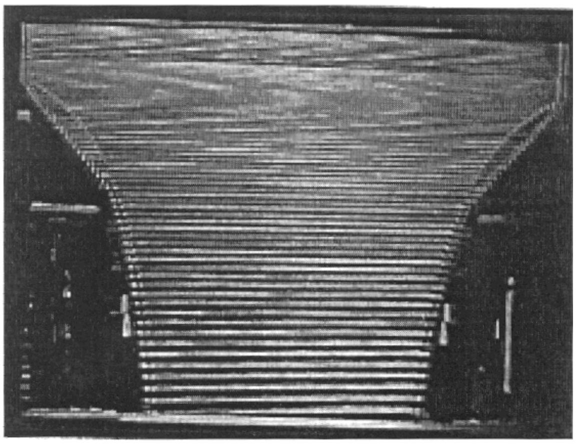

Figure 2: Echellogram: Off-axis echelle spectrum

With any optical system the use of higher orders will provide better resolution, smaller wavelength range (for that order) and an increased background due to stray light. This phenomenon is especially found with multiple order systems. Increased background causes more noise and poorer precision, especially with low signals as observed with low concentrations. The stray light of echelle optics is especially high due to the very high orders used. This in turn affects the detection limit.

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The two dimensional echelle spectrum has a variable resolution that can be fairly good in the UV region. However, one characteristic of echelle optics is that the resolution gradually changes with wavelength. The prism usually used produces the highest resolution in the UV region but for the lower orders (higher wavelengths) they have much poorer resolution, sometimes, almost a factor of 10 times worse.

Resolution is accepted by all to be very important in ICP-OES. However, terms like “pixel” resolution, when used with SSD spectrometers can often raise confusion compared to the classical definition of full width at half height (FWHH) or peak valley methods. In SSD spectrometers using echelle optics, a peak will typically be characterized by 3-4 pixels, so for example, a 7 pm “pixel” resolution spectrometer might yield twice that figure when using the FWHH definition of optical resolution. This can be seen in classical resolution tests of As/Cd at 228.802 nm (Figure 3). Mathematical corrections can improve detection limits in some cases, but usually it corrects for problems created by optical deficiencies.

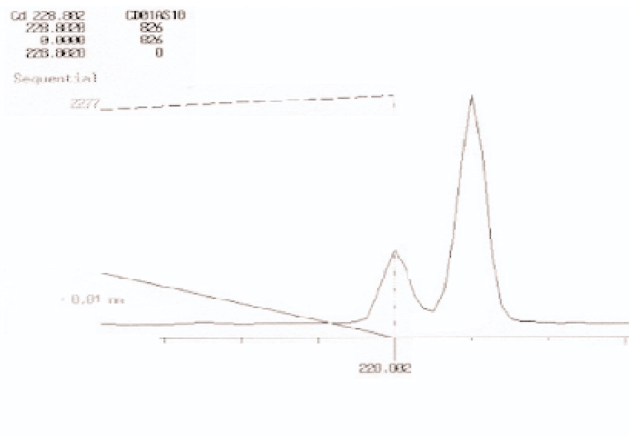

Figure 3: As/Cd with 5pm optical resolution as acquired on a JY ULTIMA 2 ICP-OES.

Another characteristic of echelle optics is that an aberration occurs causing a blurred image on the edge of the bell shaped spectrum. This leads to a light loss (less light per pixel) and poor resolution compared with wavelengths in the center. Therefore, with these echelle spectrometers a resolution of 10 pm can degrade to 25 pm at the edge, even though it may be less than 2 nm away. This phenomenon will show as poor detection limits and resolution for that particular elemental wavelength.

Even on classical optics the resolution can change as the wavelength range limit is reached. For high resolution, either a very high-density grating is used e.g. 4320 g/mm, or several grating orders are used with order sorting by means of a solar blind PMT or filters. Either option gives a restricted wavelength range for a given resolution. For example, a 4320 g/mm grating will have a range of 120-450 nm on 1 meter optics. A 2400 g/mm grating on the same optical system using 2^{nd} order will cover 120-320 nm, while 1^{st} order will cover the high wavelengths of 120-800 nm.

As mentioned earlier, the echelle uses multiple orders and wavelength-efficiency curves can be described as “order hopping”, as shown in Figure 4. These echelle characteristics give signal “holes”, just before and just after the order hop, where the signal intensity is low. In the UV region, this order hopping may occur every 4 nm.

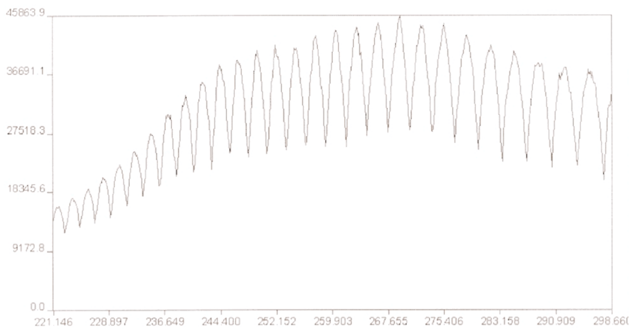

Figure 4: Echelle optics "order hopping" spectrum from a constant light source.

Note the degraded resolution with wavelength, and the amplitude of the intensity peak to valley.

Due to order hopping, the slit height of the echelle spectrometer must be small in comparison with classical optics. If a normal slit were used e.g. 6-8 mm, the spectrum from the various orders would merge together giving spectral overlap and gross interferences. For this reason an echelle SSD spectrometer will typically use 0.2 mm slit height. Even though an echelle spectrometer can use wider slits than classical optics, the difference in slit height leads to a large difference in total light throughput to the detector between the two optical systems. Figure 5 shows a comparison of energy at different slit heights.

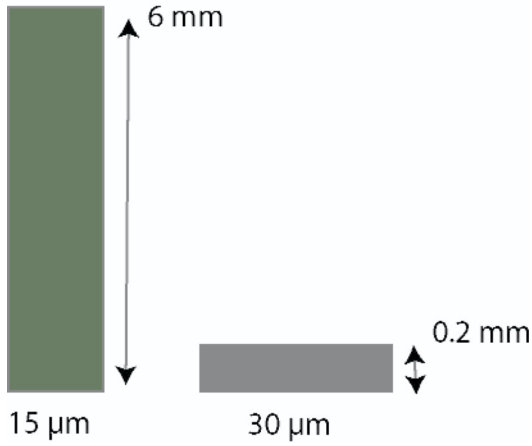

Figure 5: Slit height and energy comparison

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