Imaging Spectrographs

Understanding Tangential and Sagittal Focal Planes
Helps to Optimize Spectrograph/CCD Performance for Your Application

Introduction

Optical spectroscopic data acquisition has entered a new dimension with the introduction of fiberoptic cables and two-dimensional detector arrays, such as CCDs. To a spectroscopist an elongated skinny image of a point source has always been more beautiful than a round "visually true" image that photographers would appreciate. Now however, the spectroscopist is faced with the possibility of spatially discriminating spectral information along the length of his entrance slit. He must now understand the compromises in both spectral and spatial resolution that can be made and adapt his definition of a beautiful image to his expanded capabilities and experimental needs.

History

A spectrograph in the most general terms is a device that will reimage an illumination source at its entrance into a series of images, one for each of the constituent wavelengths of light, dispersed across a focal plane. A detector is placed in the focal plane to record the position of each of the images. The position of the image on the focal plane can be used to mathematically determine the wavelength of light present in the source. Thus all spectrographs are imaging systems wherein optical imaging elements are used in conjunction with a wavelength dispersing element to produce a spectrally dispersed image of the source.

The first spectrographs consisted of refractive convex lenses and prisms. The dispersed images were captured on photographic plates. The spectral images were analyzed with micrometers and, eventually, densitometers to calculate wavelength and intensity information. Today most spectrographs use concave reflective optics and diffraction gratings. See Figure 1. Solid state linear and two dimensional arrays are used to acquire the spectral data for processing via computer.

Key Criteria

The key performance criterion of any spectrograph is its ability to discriminate spectral images of the source. This criterion, resolution, is usually stated in terms of wavelength units such as nanometers. A spectrograph with a resolution of 1nm can discriminate spectral images of the source with a wavelength difference of 1nm. If the source emits (or absorbs) multiple wavelengths closer together than 1nm, they will not be resolvable. The resolution is a function of the dispersion of the spectrograph, usually stated in nanometers per millimeter, and the imaging quality of the optics.

The dispersion of a spectrograph is a function of the groove density of its gratings and its focal length. Given two spectrographs with the same focal length, doubling the groove density will double the dispersion, and theoretically the resolution. Given two spectrographs with gratings having the same groove density, doubling the focal length will double the dispersion and theoretically double the resolution. These improvements are theoretical because there are inherent geometric optical limitations that affect the quality of the image. These include, astigmatism and coma, which blur the image as a function of the distance from the central axis (the imaginary line that passes from the center of the entrance slit, through the center of the optical elements to the center of the focal plane).

The aperture of an optical system defines its ability to gather light. The larger the aperture, the more light can be directed to the detector, thus improving the throughput or sensitivity of the spectrographic system. Aperture is usually stated as f/ number. In practice it is a measure of the ratio of the diameter to the focal length of the smallest optical element in the system. An f/4 spectrometer with a focal length of 300mm would have mirrors that are 75mm in diameter.

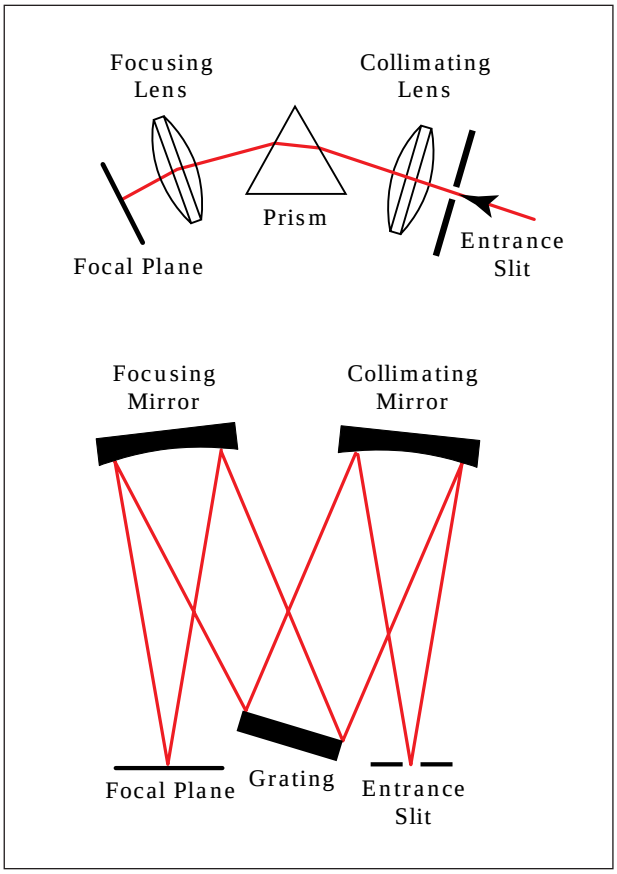

Figure 1

A smaller aperture, f/8 300m spectrometer would have 37.5mm diameter mirrors, and would have 1/4th the light gathering power. Unfortunately there is a price to pay for light gathering power and that is increased severity of the aberrations due to the acceptance of more rays further off the optical axis. The larger the aperture of the system, the worse its imaging properties. With degraded imaging comes reduction in the ability to separate images in the focal plane. Given two spectrographs of the same focal length, with the same gratings, but with different apertures, the one with the larger aperture will have lower resolution because the greater number of off-axis rays more severely distort the image of the source. There is a fundamental trade off between resolution and throughput in spectrograph design. A large aperture system can however be "apertured" or "masked down" by under-filling its optics to improve its imaging quality, resulting in improved spectral and spatial resolution.

Spherical Aberrations

Astigmatism is the elongation of an image. With spherical optics a point source will be elongated into two line images and one visibly focused "true" image. One line image will be vertical with a width close to the diameter of the point, the other will be horizontal with a height close to the diameter of the point. These images are separated in space. For all other imaging applications the plane of best image quality is somewhere between these two points, where there is the closest convergence of all of the rays. The elongated images fall on two focal planes, one called the tangential and the other called the sagittal. See figure 2. In classical spectrograph design, the detector is placed in the tangential focal plane as it is horizontal imaging quality that affects the ability to resolve wavelengths. The spectroscopist is not concerned with the two dimensional visual beauty of the image but rather having the sharpest image quality in the plane of spectral dispersion.
Coma is the smearing or blurring of an image. A point source is smeared to a shape similar to a comet. The amount of smearing is a function of off-axis rays composing the image. The larger the aperture of the spectrometer the greater the coma as more off-axis rays are captured. See figure 3. Traditional spectrometer designs employ spherical mirrors. In spherical optics the tangential and sagittal foci are well separated and there is little curvature of the focal planes. All other parameters being equal, i.e. focal length, grating density, and aperture, a spectrograph with spherical optics will give better, more uniform resolution than the imaging spectrographs described below. See Figure 4.

Imaging Spectrographs

Before the development of two dimensional detector arrays, such as CCD's, and fiber optics, spectroscopists were only concerned with the imaging quality in the plane of the spectrograph's dispersion. Whether the images were points or

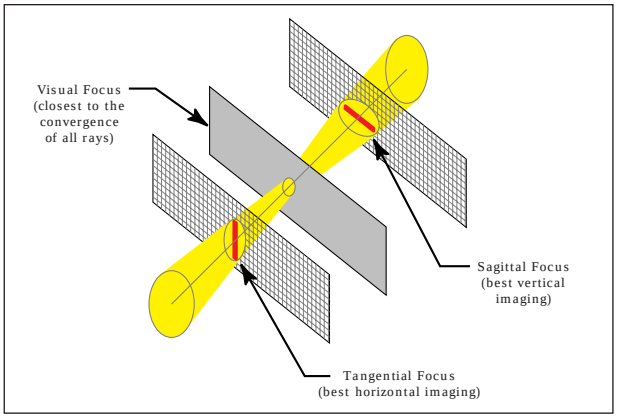

Figure 2

lines, as long as they were narrow as possible, the highest resolution measurements could be made. Even though an image of a point on the entrance slit was vertically elongated several millimeters, it did not affect the spectral measurements. Spectrometers were designed place the detectors in and parallel to the tangential focal plane. With the advent of two dimensional arrays and fiber optics however, new possibilities in analyzing spectral information spatially distributed vertically along the entrance slit of the spectrograph became possible.
The vertical astigmatism that previously was not a significant issue now would smear the data from nearby sources in the entrance slit plane. If the light were carried by fiber optic cables from spectroscopically different sources, their spectra would overlap and would be mixed. Spectrographs had to evolve to take into account both horizontal and vertical image quality.
A new breed of "imaging spectrographs", those that could spatially differentiate points along the entrance slit of the spectrograph was developed. See figure 5. Instead of using only spherical mirrors toroids are employed. Toroids have different horizontal and vertical radii of curvature. This effectively brings the tangential and sagittal focal planes closer together. The planes in fact intersect on the optical axis; the image of a point source on the optical axis will show virtually no

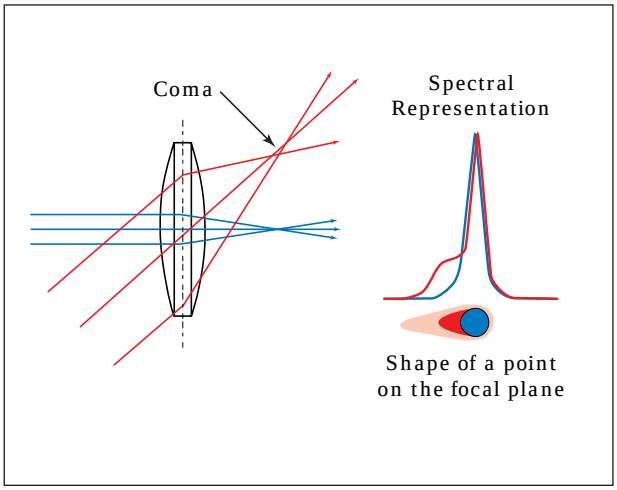

Figure 3

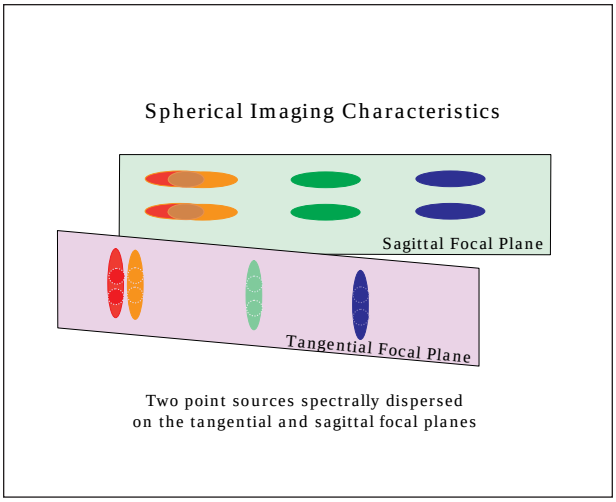

Figure 4

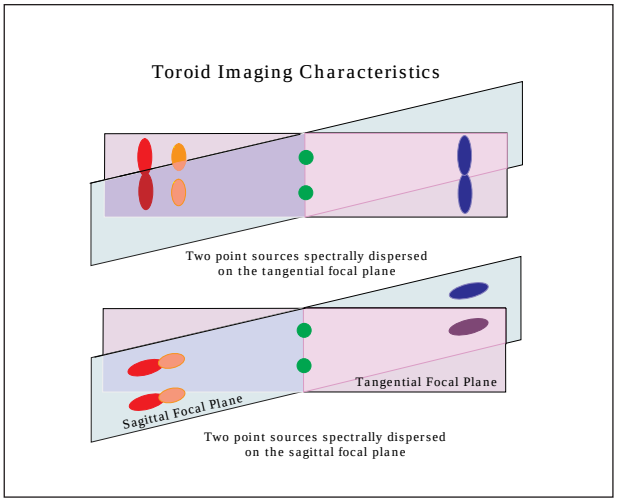

Figure 6

horizontal nor vertical astigmatism. The planes are however inclined to each other and also to the normal of the optical axis. See figures 6 and 7. As the focal planes are inclined and closer together, the level of astigmatism varies across chosen focal planes. If a detector is placed in the tangential focal plane, in order to maximize horizontal imaging quality and therefore spectral resolution, the vertical imaging quality will degrade with displacement off axis as the two focal planes diverge. The level of astigmatism over the entire focal plane is significantly less however than that of a spectrograph employing only spherical mirrors.
If the detector is placed on the sagittal focal plane the vertical image quality will be maximized, images of individual fibers will remain essentially the same height. If the detector is placed in this plane however, the horizontal image quality will be

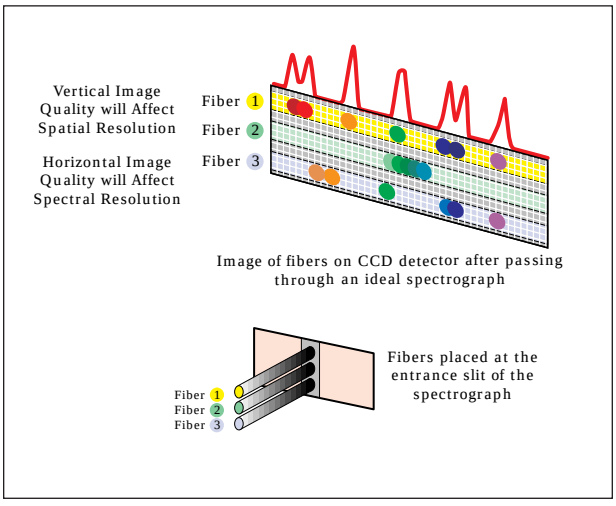

Figure 5

significantly reduced; that is the spectral resolution will no longer be constant across the focal plane. Spectroscopically this could be detrimental to certain analytical measurements such as concentration, bandwidth and power.
In as much as having best spectral resolution and spatial resolution are mutually exclusive, the system designer or user may make a decision as to weighting system performance in favor of one parameter or working with the detector at an angle that compromises spectral resolution for some gain in vertical imaging quality. A wedge shaped adapter can be employed to do this. The question is, under what circumstances is the compromise appropriate.

Practical limitations in working with an imaging spectrograph

Ten micron diameter fibers exist. Assuming a CCD detector with a height of 6.7mm, it would be possible to place 670 fibers along the entrance slit. Could each fiber be read out as a distinct spectral source? Unfortunately not. The analysis is not only limited by the spectrograph aberrations but also by the detector. And in most cases it is the detector that ultimately limits the spectral resolution of the system.
Most CCD detectors used for spectroscopic analysis have pixels that are approximately 26µm square. This is the limiting resolving element in the system. Two contingent 10µm fibers would not be differentiated by the detector. See figure 8.

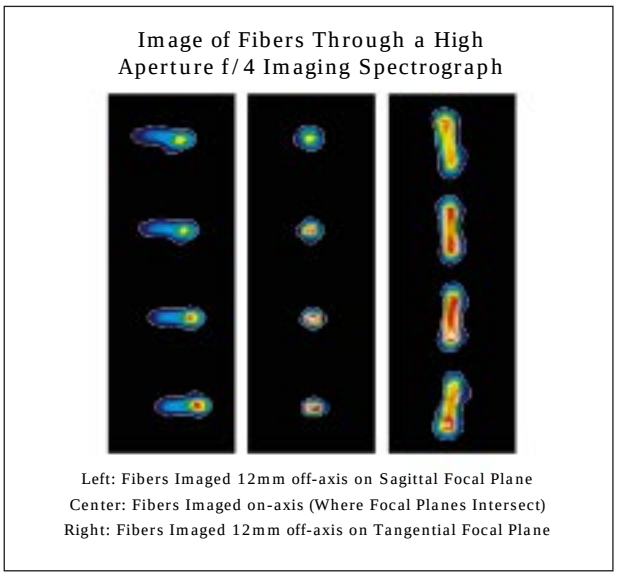

Figure 7

Even if the spectrograph had perfect imaging the 670 spectra could not be collected. In reality crosstalk between pixels is such that the minimum effective resolution element is approximately 75µm. Therefore working with fibers much smaller than that would not give any consistent spectral resolution gain, and would penalize throughput. For most practical, high energy, spectroscopic application such as transmission measurements, emission measurements, and strong fluorescence,100µm diameter fibers are the minimum diameter recommended. As a practical point, 200µm fiber are a better choice if the resolution permits, as they are more rugged.

Beautiful Images

In working with short focal length high aperture imaging spectrographs, in the 300mm focal length f/4 aperture range, the application usually will determine whether the spectral or spatial resolution will be the limiting factor. In resolution critical applications such as Raman spectroscopy, most emission spectroscopies, and some fluorescence, it will be imperative to get the narrowest image possible, i.e. placing the detector in the tangential focal plane. Since the vertical astigmatism will be greatest there, the images of the fibers will be elongated to approximately 800µm at the extreme corners of a 26mm by 6.7mm focal plane. Practically up to six 200µm fiber inputs could be monitored without any crosstalk at full aperture with the above mentioned spectrograph. (Reducing the aperture would increase the number of fibers that could be monitored but with a reduction in throughput.) For these applications a taller skinny image is still beautiful. See figure 9.

In other applications such as absorption and transmission measurements, reflectivity, photoluminescence and most fluorescence, the natural bandwidths of the peaks are quite broad and the spectral resolution will not be critically affected by horizontal astigmatism. In these applications, if the spectroscopist were interested in monitoring the maximum number of fiber inputs, a detector might be placed in the sagittal focal plane where the heights of the fiber images would be less distorted. He could then safely monitor up to twenty 200µm fibers. Under these circumstances, short fat images are beautiful. See figure 10.

Using an angled adapter to place the detector in an intermediate, compromise position, will produce rounder images of the fibers. If less than 6 fibers are to be analyzed, using the adapter will only decrease spectral resolution. If more fibers are necessary, it may be better to mask down one of the mirrors to about f/6. This will greatly improve the image quality and permit up to 10 fibers to be analyzed. If ten or more fibers are to be analyzed and throughput becomes a limiting issue, than using the adapter plate is appropriate.

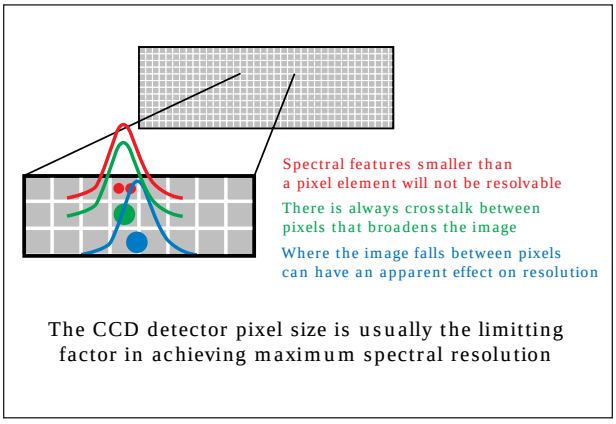

Figure 8

Conclusion

Ultimately the spectroscopist must understand the performance trade-offs of his system. They boil down to the classic “choose two out of three” situation. The choices are:

1. **Spectral Resolution**
2. **Spatial Resolution**
3. **Throughput**

- For high spectral resolution and throughput, use the tangential focal plane.
- For high spectral resolution and improved spatial resolution, reduce the aperture (and throughput).
- For highest spatial resolution use the sagittal focal plane at the expense of spectral resolution.
- For the above mentioned spectrometers, in those applications where the spectral resolution requirement falls between 1 and 5nm, and more than ten fibers are to be monitored, use an angled adapter. This positions the CCD on or near the sagittal focal plane.

Figure 9

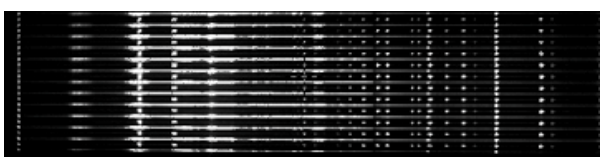

Figure 10

Imaging spectrographs are capable of producing very beautiful images. The spectroscopist should let his application and not his eyes determine what is beautiful. Understanding the imaging characteristics of a spectrograph leads to a greater appreciation of this beauty and also to higher quality spectra.

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