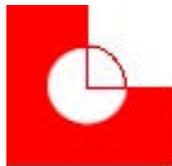


Application Note (A11)

Slit and Aperture Selection in Spectroradiometry

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Introduction

Selection of appropriate slits and apertures is critical in obtaining correct spectroradiometric results, and yet remains a subject fogged in mystery for most users. This section aims to help dispel that fog, giving the user a clear insight as to which slits or apertures should be selected for their particular application.

Monochromator slits are rectangular, generally much taller than they are wide, and are positioned so that the long side is normal to the plane of the monochromator (i.e. usually vertical). An aperture may be any shape, though it is usually circular, and is used in place of a slit in certain applications. For the purpose of this discussion, circular apertures will be assumed, since these are the most common and represent a very different shape than that of a slit.

Input or exit optics will frequently require a circular aperture to define a field-of-view (telescopes, microscopes and other imaging optics), the beam convergence/divergence and uniformity (collimating optics), or the size of an image (some reflectance, transmittance or detector response accessories). Generally, the only accessories that do not require apertures are non-imaging types such as integrating spheres. **The requirements of the input/exit optics always determines the selection of an aperture or slit.** If the accessory attached to the entrance requires an aperture, then it is installed in place of the entrance slit; if the accessory attached to the exit requires an aperture, then it is installed in place of the exit slit.

Theoretically, two apertures may be installed - at both the entrance and exit slits. However, such a configuration requires exact alignment of heights, and is subject to large changes in throughput with small changes in temperature, flatness of benches etc. This inherently unstable arrangement is therefore rarely used, except in special applications, and generally whichever side of the monochromator that is opposite the accessory should always have a slit installed.

The Concept of Limiting Aperture

For large sources or non-imaging optics, the entrance aperture (or slit) limits the size and distribution of light entering the monochromator. However, for certain other applications, the size and distribution may be limited by other factors, making the selection (or indeed the presence) of the slit or aperture irrelevant.

In certain applications, e.g. spectral radiant intensity measurements, the aperture must be under-filled. This means that the aperture no longer defines the size or shape of the image entering the monochromator. An "equivalent aperture", having the same size and shape as the image, should then be used to determine the expected behavior of the system.

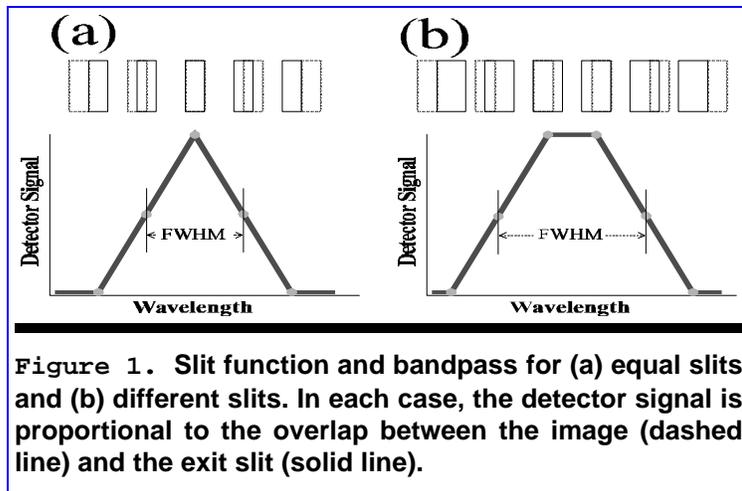
Similarly, when using fiber optics (even slit-shaped fibers) the slit width or aperture only applies when smaller than the fiber. If the fiber is smaller than the slit (or aperture) it is the fiber that determines the expected behavior of the system. When using a light source which forms an image of the source onto the entrance slit, the same considerations apply.

The concept of limiting apertures can also be applied at the exit of a monochromator, since detectors may be small, e.g. a 5mm slit is the limiting aperture when using a 10 x 10mm silicon detector, but not when using a 3 x 3mm PbS detector. Even if the detector is coupled to the monochromator using imaging optics, it may still define a limiting aperture once magnification effects have been considered.

Slit-slit Bandpass and Slit function

When using a monochromatic source, the monochromator forms an image of the entrance slit at the exit. The exit slit therefore acts as a mask, defining the portion of the image that reaches the detector. As the wavelength is altered, the image moves across the exit slit, and a scan of detector signal vs wavelength is called the slit function, and may be used to find the full-width-at-half-maximum (FWHM) or, as it is more commonly called, the bandpass.

The slit function, and hence bandpass, can be calculated quite simply for an ideal instrument. Two possible shapes exist: one where the entrance and exit slits are the same, and the other where they are different. If the detector responds equally to all light passing through the exit slit then, as illustrated in **Figure 1**, the signal is proportional to the area of overlap



between the image of the entrance slit and the mask formed by the exit slit. This gives a triangular slit function for equal slits, and a flat-topped function for different slits. In the case of different slits, the image could be wider than the exit slit and still give the same result, so the slit function is independent of which slit is the entrance and which is the exit.

Although these two shapes exist, in fact only one is sensible for spectroradiometry: equal slits. This is because with different slits the throughput (and hence signal) is limited by the smaller slit while losing resolution to the

wider slit, and severe sampling errors can arise in measurements of sharp spectral features with normal scan intervals. On the other hand, equal slits provide the maximum signal at any bandpass and give accurate peak areas with most scan intervals less than the FWHM.

In a real system, the triangular function will have a rounded top and baseline intercept. Also, if the slits are very narrow, the function may often resemble a skew-gaussian curve rather than a triangle. These are due to normal aberrations found within any monochromator system and do not affect the general principles outlined.

Aperture-slit Bandpass and Slit function

As with slit-slit systems, an image of the entrance aperture is formed at the exit slit, though the resulting slit function is not nearly so obvious. The important difference for aperture-slit calculations is that the

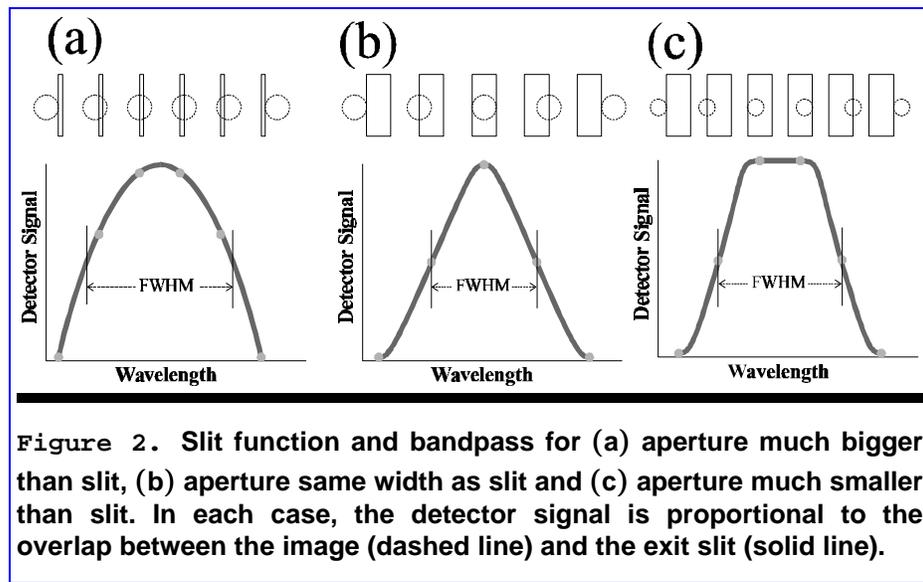


Figure 2. Slit function and bandpass for (a) aperture much bigger than slit, (b) aperture same width as slit and (c) aperture much smaller than slit. In each case, the detector signal is proportional to the overlap between the image (dashed line) and the exit slit (solid line).

shapes are sufficiently mis-matched to create three possibilities for the slit function, as shown in **Figure 2**. The first (a), where the aperture is much larger than the slit, gives a cosine-curve shaped slit function. The second (b), where they are the same width, gives an almost triangular shape (except the sides are "S-shaped") with essentially the same bandpass as the slit-slit equivalent. The third option (c), where the aperture is much smaller than the slit, gives a flat-topped profile with "S-shaped" sides.

For exactly the same reasons as those applying to slit-slit configurations, best results are obtained by matching the slit and aperture widths as closely as possible. However, since the size of the aperture and slit are normally determined by additional factors such as field-of-view and sensitivity, it is not unusual to make measurements with the slit larger than the aperture. There are **no** circumstances where slits much smaller than the aperture give better results than matched combinations.

Although the above description used a aperture entrance and slit exit, the same results would be obtained if they were reversed since we are treating the monochromator as ideal. In real systems, very slight differences may exist between the two configurations since aberrations will distort the images of slits and apertures differently.

Dispersion, Bandpass and Limiting Resolution

The previous section dealt with the shape of the slit function. However, to put actual values to the bandpass the dispersion must also be known. The dispersion (or more correctly inverse-linear-dispersion) is the wavelength region (in nm) in 1mm distance in the plane of the slit. It varies with the focal length of the monochromator and the grating groove density (grooves per millimeter). For any particular monochromator, if the dispersion with a 1200 g/mm grating is known (this is usually available from the manufacturer), the bandpass with any grating or slit width can be calculated using:

$$B = \frac{1200 \cdot D \cdot S}{G}$$

- where: B is the bandpass in nm
- D is the dispersion in nm/mm with a 1200 g/mm grating
- G is the groove density of the grating used in g/mm
- S is the slit width in mm.

Thus, if a 600 g/mm grating is used with a monochromator of 4 nm/mm dispersion and 1.25 mm slits, the bandpass will be 10 nm. **Table 1** shows the bandpasses of various slit-slit combinations (for an OL 750 single monochromator and 1200g/mm grating), highlighting the recommended (equal entrance and exit) selections.

Entrance [mm]	Exit slit [mm]				
	0.25	0.5	1.25	2.5	5.0
0.25	1.0	2.0	5.0	10.0	20.0
0.5	2.0	2.0	5.0	10.0	20.0
1.25	5.0	5.0	5.0	10.0	20.0
2.5	10.0	10.0	10.0	10.0	20.0
5.0	20.0	20.0	20.0	20.0	20.0

Table 1. Bandpasses (in nm) for various slit-slit combinations for an OL 750 single monochromator and 1200g/mm grating. Recommended combinations are highlighted.

The above equation is based on two basic assumptions: that the dispersion remains constant with wavelength and is perfectly linear at all slit widths. Real systems have a variable dispersion with wavelength, though good designs can optimize this to just a few percent, and aberrations and alignment errors generally limit the bandpass at small slit widths. This limit at small slit width is called the limiting optical resolution of the system. Spectroradiometric measurements are generally made at bandpasses well above the limiting optical resolution of the system to ensure that the slit function is reasonably constant at all wavelengths.

Because the slit function changes with the relative size of the aperture-slit combinations, mis-matches (even to smaller widths) can lead to increased bandwidths. This means that the above formula for slit-slit combinations will not apply to aperture-slit sizes. **Table 2** shows the bandwidths of various aperture-slit combinations (for an OL 750 single monochromator and 1200g/mm grating), with the recommended configuration highlighted.

Aperture diameter [mm]	Exit slit [mm]				
	0.25	0.5	1.25	2.5	5.0
1.5	3.8	3.6	4.0	7.5	15.0
3.0	7.7	7.6	7.3	8.1	15.0
5.0	13.0	12.9	12.3	12.2	15.0

Table 2. Bandpasses (in nm) for various aperture-slit combinations for an OL 750S and 1200g/mm grating. Recommended combinations are highlighted.

The above equation is based on two basic assumptions: that the dispersion remains constant with wavelength and is perfectly linear at all slit widths. Real systems have a variable dispersion with wavelength, though good designs can optimize this to just a few percent, and aberrations and alignment errors generally limit the bandpass at small slit widths. This limit at small slit width is called the limiting optical resolution of the system. Spectroradiometric measurements are generally made at bandpasses well above the limiting optical resolution of the system to ensure that the slit function is reasonably constant at all wavelengths.

Because the slit function changes with the relative size of the aperture-slit combinations, mis-matches (even to smaller widths) can lead to increased bandwidths. This means that the above formula for slit-slit combinations will not apply to aperture-slit sizes. **Table 1.7** shows the bandwidths of various aperture-slit combinations (for a single monochromator with 4 nm/mm dispersion), with the recommended configuration highlighted.

Table 0.1 Bandpasses (in nm) for various aperture-slit combinations for a single monochromator with 4 nm/mm dispersion. Recommended combinations are highlighted.

Aperture diameter [mm]	Exit slit [mm]				
	0.25	0.5	1.25	2.5	5.0
1.5	3.8	3.6	4.0	7.5	15.0
3.0	7.7	7.6	7.3	1.1	15.0
5.0	13.0	12.9	12.3	12.2	15.0

Throughput vs Bandpass

Optimizing practical measurements often involve a trade-off between smallest bandpass and highest signals. If there are fixed parameters, such as field-of-view, that must be observed, the slit/aperture configuration will also be fixed. However, if several combinations are possible, then the system may be optimized. Assuming that the slits and apertures are matched, as recommended, and the entrance slit (or aperture) is uniformly illuminated, the signal increases with width. The magnitude of this increase varies with the type of source and whether slit-slit or aperture-slit combinations are used. If the source is a broad-band type, such as a tungsten lamp, doubling the slit-slit sizes would give a four-fold increase in signal. Under the same conditions, an eight-fold increase would be seen for aperture-slit combinations (since both width and height of the aperture are doubled). When a monochromatic source such as a mercury lamp is used, only a two-fold and four-fold increase is seen for the respective slit-slit and aperture-slit combinations. This difference between monochromatic and broad-band sources accounts for the observed changes in the spectra of mixed sources, such as fluorescent lamps, as the bandpass is altered.

Double Monochromators and Middle Slits

The above sections deal with entrance and exit slits and apertures for a single monochromator. The basic principles also apply to double monochromators, but with modifications. Essentially, a double monochromator is two identical single monochromators working in series, but using a single drive mechanism and housing. Theoretically, and sometimes practically, double monochromators have four slits - an entrance and exit for each of the single monochromator components. More generally, the exit of one is the entrance of the other and hence only three slits are used - the entrance, middle and exit. The influence, and hence selection, of the middle slit largely depends on whether the double monochromator is additive or subtractive.

The majority, by far, of double monochromators in use are additive. Additive means that light that is dispersed by the first monochromator component is

further dispersed by the second. Thus, if a single monochromator has a dispersion of 4 nm/mm, then a double additive monochromator of the same basic design would have a dispersion of 2 nm/mm. When using **Tables 1 and 2** for the OL 750D systems, the bandpass calculated should be divided by 2. However, even though both monochromator components share the same drive and housing, links and gears can mean that each part may not transmit exactly the same wavelength (this is commonly referred to as "coordination" of the monochromators). If this happens, the throughput of the system will suffer, and if this wavelength mis-match is temperature dependent (as it is in all practical systems) then it is inherently unstable and unsuitable for spectroradiometry. Compensating for this is actually quite easy: the middle slit should be at least 1 to 2 mm bigger than the entrance and exit whenever possible. Apertures are **never** used in the middle slit position.

Subtractive monochromators have two main applications. The first of these is performing extremely fast measurements, of the order of picoseconds. Here, the difference in path lengths through an additive monochromator might spread out a pulse because of the finite speed of light, but the symmetrical arrangement of a subtractive double monochromator provides a constant length for all paths. The second application, for measurements such as detector spectral response, is more common. In additive double monochromators, the small difference in wavelength between the left and right edges of the slit can cause serious errors if the detectors are not uniform. However, the subtractive double monochromator has no residual dispersion at the exit slit, eliminating this source of error. The lack of residual dispersion is because the second component monochromator operates, not to further disperse like an additive system, but to combine (the opposite of disperse in this context) any light dispersed by the first component monochromator. This means dispersion effectively only occurs in the first component monochromator, and this system should be treated as a single monochromator using the entrance and middle slits as far as slit function, bandpass etc. is concerned. However, the coordination of the two components are still important, and since there is no effective movement of the image at the exit slit, it is prudent to:

- i. have the entrance slit slightly larger than the exit slit (or aperture).
- ii. have the middle slit slightly larger than the entrance slit.

These conditions are to optimize stability, which is essential for good spectroradiometry, but they do compromise the narrowest bandpasses and triangular slit function. If a triangular slit function is required, equal entrance and middle slits should be chosen. If the narrowest bandpass is also desired, then the entrance and middle slits should be equal to the exit slit/aperture (but beware of the inherent instability of such an arrangement).