

Application Note (A7)

Errors in Spectroradiometric Measurements Using Multi-channel Detectors

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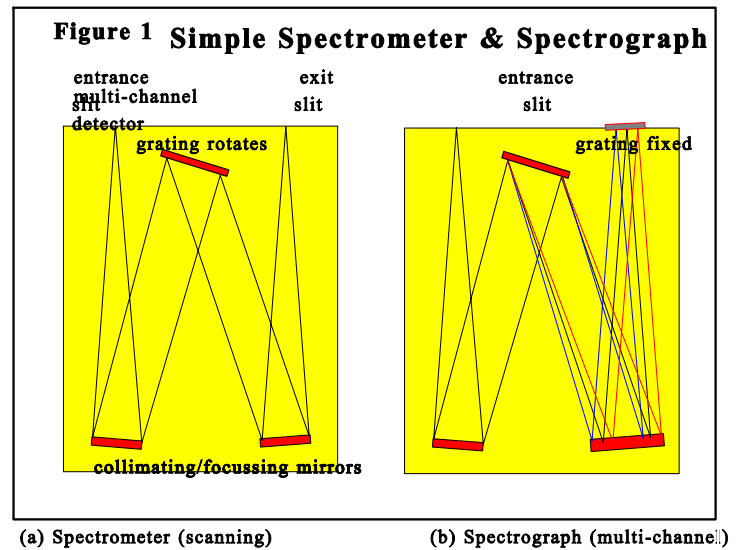
Errors in Spectroradiometry Using Multi-Channel Detectors

Spectroradiometry is the measurement of the distribution of energy of electromagnetic radiation with respect to wavelength. To achieve this, a spectrometer is used to isolate energy within a given bandpass. It is important that both the width and shape of the bandpass remain constant over the entire range of measurement to obtain correct results. This article describes important parameters in radiometric measurements and compares results obtained using scanning and multi-channel systems.

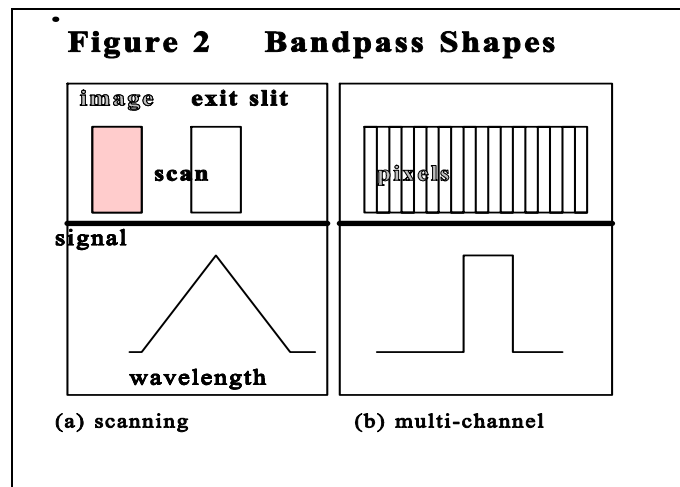
Multi-channel detectors such as charge-coupled devices (CCD) and photo-diode arrays (PDA) can, under certain circumstances, improve the sensitivity of many spectroscopic methods, allowing measurements to be made in much shorter times. Manufacturers of spectrographs and multi-channel detectors have recently made claims that their equipment may be used in spectroradiometric applications. While it is possible in theory to produce meaningful spectroradiometry from such systems, the practical difficulties are generally ignored by manufacturers in their sales information, system implementation and data treatment.

Before proceeding with a detailed comparison it is useful to visualize the ways in which spectrographs differ from spectrometers, and multi-channel detectors differ from single detectors of the same material.

Figure 1 shows typical designs of (a) spectrometers and (b) spectrographs. The two instruments look very similar but there are important differences as far as spectroradiometry is concerned. In a spectrometer the grating rotates to bring each wavelength in turn to the exit slit, keeping a constant optical path through the system and a nearly constant bandwidth. In the spectrograph each wavelength hits a different part of the detector and hence has a different optical path, leading to a highly variable bandwidth and band shape. As the physics of spectrometers and spectrographs are largely identical one might expect similar results, but differences arise from the geometry of the detectors. These differences arise from the fact that in scanning systems the entrance and exit slits are the same, whereas the spectrograph has no exit slit and instead uses the size of individual pixels.



In Figure 2, the two types of operation are shown for a single monochromatic line source. In 2(a), the image of the entrance slit moves across the exit slit giving a triangular profile. In 2(b) the image falls on several pixels giving an almost rectangular profile. To reveal the most basic reason why multi-channel detectors are misused in spectroradiometry one need only think of what happens as the slit width is changed when looking at monochromatic sources. If the slit widths are doubled in a scanning system the signal doubles. In a multi-channel system the width of the rectangle doubles as the entrance slit is doubled but the signal at the top of the rectangle **stays the same**. In contrast, for broadband sources such as those used to calibrate the system, the signal **does** double as the entrance slit width is doubled. Since the signal detected at each pixel depends not only on the intensity of the source, but also its distribution (whether it is monochromatic or broad-band), it is obvious that *a simple wavelength-for-wavelength comparison, as used by most suppliers of multi-channel systems, is inappropriate*.

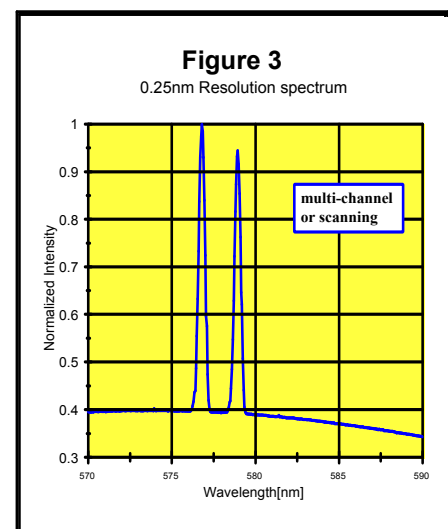


To compare classical (scanned) and multi-channel approaches to spectroradiometry, the following aspects should be considered:

- *Bandpass*
- *Dynamic range*
- *Stray light*
- *Wavelength accuracy*
- *Resolution*
- *Multiple orders*
- *Non-linear effects*

Bandpass

A multi-channel detector requires a spectrograph to be used so each wavelength takes a different optical path. Thus, the bandpass and aberrations at each pixel are different. Also the pixels themselves act as the exit slit and are generally much smaller than the entrance slit so the "bandpass" is not particularly well defined. These effects may not be evident, especially if **similar continuous** sources are compared, but inspection of line sources readily shows that the results are not as they should be. Figure 3 shows the 577 and 579nm peaks of



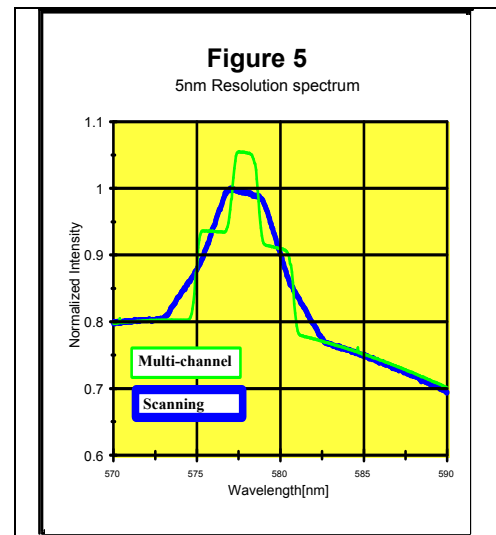
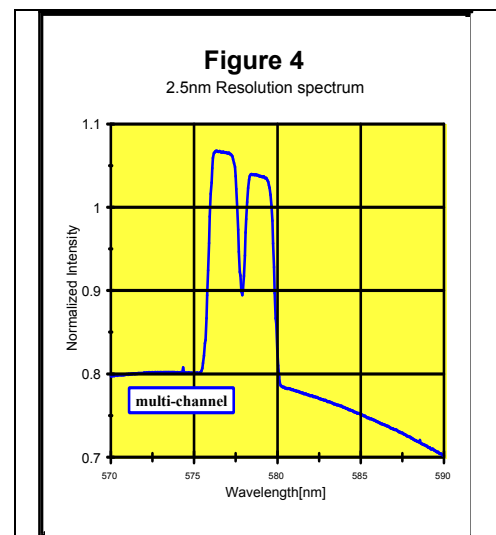
Mercury resolved at 0.25nm as would normally be encountered in a scanning system or multi-channel system with very narrow entrance slit. As slit widths of scanning systems are increased both height and width increase, retaining the triangular shape. For multi-channel systems however the "exit slit" is fixed as the pixel size so only the width increases, giving a "square topped" appearance as seen in Figure 4. As slit widths are further increased in the scanning system the triangular profiles merge to give a single peak as shown in Figure 5. In contrast the multi-channel system produces a "third peak" half way between the two real peaks. From the preceding discussion it is obvious that interpretation of multi-channel results is difficult for any line or mixed sources. In fact the multi-channel approach is likely, by the very nature of the technique, to distort the spectrum of any lamp that does not have an identical spectral distribution to the calibration standard.

Dynamic range

Often when measuring a source the signals obtained may be many orders of magnitude. In order to obtain good results at low signals yet not saturate at high signals most scanning systems have autoranging facilities. Multi-channel devices cannot change ranges or integration time during acquisition so the user is limited to the inherent range of the analog-to-digital converter. Most good multi-channel systems have 14 or 16 bits and so the full dynamic range is only 3 or 4 magnitudes. This compares to 6 to 10 magnitudes commonly found in scanning systems.

Stray light

On single spectrometer systems stray light often limits the lowest light level measurable, especially in the UV. Spectrographs, by virtue of having no exit slit, generally exhibit much higher stray light levels than single spectrometers, which in turn severely limits their use in the UV. Double spectrometers may be used to drastically cut down stray light in scanning systems but they are not compatible with multi-channel detectors. In measuring sunlight or solar simulators in the UV this stray light reduces the usable dynamic range of multi-channel systems to 1 or 2 decades making it totally unsuitable for such work.



Wavelength accuracy

Because a multi-channel detector is used without moving the monochromator during acquisition the results should really be represented by a histogram. Like any other histogram, there is no information as to distribution within an element. With multi-channel detectors therefore any claim of accuracy better than one pixel is inferred rather than measured, and accuracies of better than half a pixel assumes detailed knowledge of line shapes. Since in most systems the multi-channel detector and spectrograph would be optimized to give wide coverage, each pixel might represent 1nm or more, and hence the wavelength accuracy is limited. In contrast, scanning systems are limited only by the step resolution and mechanical reproducibility, which is generally a very small fraction of a nanometer.

Resolution

The size of individual elements of a multi-channel detector is generally about 0.025nm. Sensible entrance slits for spectroradiometry should be in excess of 0.1mm to ensure diffraction effects are unimportant. This means that the resolution of such a system is at least 4 pixels and, bearing in mind the need for wide coverage, will give several nanometers as the best resolution (smallest bandpass) that may be obtainable. Whenever a sharply changing source e.g. sunlight, Xenon lamps etc. are to be measured the bandpass should be 1nm or less to give accurate results. In contrast, scanning systems can usually offer sub-nanometer bandpasses without compromising performance.

Multiple order effects

With any grating system such as spectrometers or spectrographs multiple order diffraction will be encountered and must be eliminated to obtain correct results. With scanning systems these multiple orders are easily removed by stopping at the appropriate wavelength, changing a filter, and then continuing the scan. This procedure cannot be adopted efficiently with multi-channel detectors, and in fact most suppliers **ignore** the problem entirely, leaving the customers to decide if they can trust the results. Other, more informed suppliers adopt a method of coating the multi-channel array with filter materials in appropriate sections. Unfortunately many of these coatings are very thin and do not block efficiently, and the systems that utilize this technique take no account of the sudden discontinuities introduced at the edges of the coating.

Non-linear effects

In scanning systems the spectroradiometric output of unknown sources is determined by comparison to a standard. Under set conditions the ratio of the signal measured to the light input is determined at each wavelength and this array of numbers represents the response of the system. For a multi-channel detector this array of numbers is complex since, in addition to transmission variations of the spectrograph with wavelength, there are many individual detectors and each has its own response. At each "central" wavelength the ratio of signal measured to light input must take account of:

- *transmission of the spectrograph*
- *variation in the transmission at different optical paths*
- *aberration changes with wavelength and optical path*
- *dark signal from each detector*
- *spectral responsivity of each detector*
- *all of the above as variations with height when using a CCD*
- *effect of the entrance slit width on the "bandpass" of the system.*

Each of the above would be expressed mathematically as a one or two dimensional array of numbers. To represent all effects properly and hence produce correct energies at each wavelength, up to 14 dimensional arrays are needed, which in turn requires long complicated calibration procedures. The single dimension arrays, currently employed in most multi-channel systems presently available (as though they are scanning systems), are inappropriate and lead to incorrect and non-linear results.

Although multi-channel devices are thought of as a series of independent arrays there are many ways in which signals on one detector can influence another. In photo-diode arrays there is a significant (sometimes several percent) "cross-talk" where the charge on one pixel can leak to neighboring pixels. In CCDs the charge in a pixel must pass through all pixels in the column below it before it is read. If charge is not transferred from pixel to pixel with 100% efficiency "trailing" occurs. Also, charge may be added or depleted depending on the characteristics of each pixel it passes through. Great care must be exercised in interpretation of results since these artifacts are indistinguishable from real data.

Conclusion

The use of multi-channel devices in spectroradiometry involves complications and limitations not found in scanning systems. If one allows for these, it is theoretically possible to produce good results in many applications. Unfortunately, present suppliers of such systems seem to over-simplify their treatment of data, often leading to incorrect or misleading results. The fact that the inaccuracies inherent in such results may vary with measurement conditions makes recognition of correctness or incorrectness virtually impossible.