Spectrometer spectral response correction: The effect of etaloning

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1. Introduction

Spectrometers are incredibly versatile instruments that measure light intensity in terms of its component wavelengths (i.e. by colour). Low cost, fibre-coupled, spectrometers like the IS Instruments MSP1000 (right) are used in a range of fields including astronomy, chemistry and biology, agriculture, lighting to name but a few.

Different types of measurements require different experimental setups, such as fluorescence, transmission, or reflectance/absorbance spectroscopy. Depending on the type of experiment, the sensitivity to the system calibration can be critical.

For various spectroscopic applications, such as measuring relative spectral peak heights or performing absolute intensity or colour measurements, it is necessary to compensate for optical losses within the instrument. For other applications, it is only necessary to perform a relative correction, which produces a suitably shaped spectrum. This technical note discusses how incoming light is affected by the spectrometer and what corrections can and should be performed.
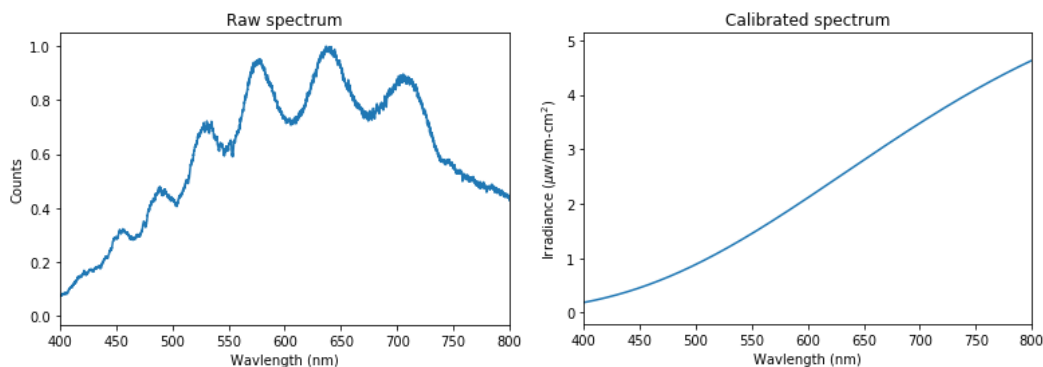

Figure 1 *(Left) A raw spectrum acquired of a tungsten halogen light bulb; (right) the same spectrum, corrected for instrument response*

Figure 1 displays the raw spectrum observed by a given spectrometer together with the response when a correction algorithm is applied. The oscillating effect observed in Figure 1 is present in many compact spectrometers, and is due to etaloning within

the instrument. The correction algorithm is a per-pixel intensity correction. The goal is to obtain a scaling factor, for each pixel on the CCD. These scaling factors correct for wavelength-dependent losses in the spectrometer. This is also called a flat field in some disciplines, such as astronomy.

This should not be confused with wavelength calibration, associating each pixel with a wavelength, which is almost always provided by the manufacturer. An instrument response correction only adjusts the number of counts received by each pixel. Some other processing steps like dark current subtraction are not wavelength dependent and should be performed routinely when a measurement is taken.

2. When should I correct for my instrument?

Although the effect displayed within Figure 1 appears dramatic, for many applications it is not necessary to correct for losses within the instrument. For example, this effect does not concern experiments that involve relative measurements. This is the case in absorption or reflection spectroscopy. Since these measurements are performed relative to a reference (for example, the spectrum of an illuminated, empty cuvette), the effect of the instrument is cancelled out.

If you are looking for the presence of a characteristic spectral peak (or peaks), but *not* their relative heights, then you typically do not need to perform an instrument correction. An example of this is wavelength calibration using a line-emission lamp.

However, if you want to make a true colour measurement, a power measurement, or you need to measure the relative heights of two peaks, it is critical that the instrument response is accurately known and corrected for. This requires a calibrated (for example NIST traceable) light source. A relative instrument correction is also possible if you have a light source with an approximately known spectra, such as a common tungsten halogen lightbulb.

2.1. Instrument response

The instrument response is governed by how all the parts within the spectrometer perform. Mirrors and the detector in a spectrometer are not perfect and have variations across their surfaces due to dust or manufacturing defects. As light enters an optical system it is absorbed and attenuated. This attenuation is wavelength-

dependent, for example a CCD has a wavelength sensitivity governed by its quantum efficiency (QE) curve.

Optical fibres and mirrors (Al or Ag coated) tend to have fairly low losses which are uniform across the (visible) spectral range of interest. The grating and detector can have more significant variations (see Figure 3). Below 400 nm, standard fibre and mirror performance degrade significantly.
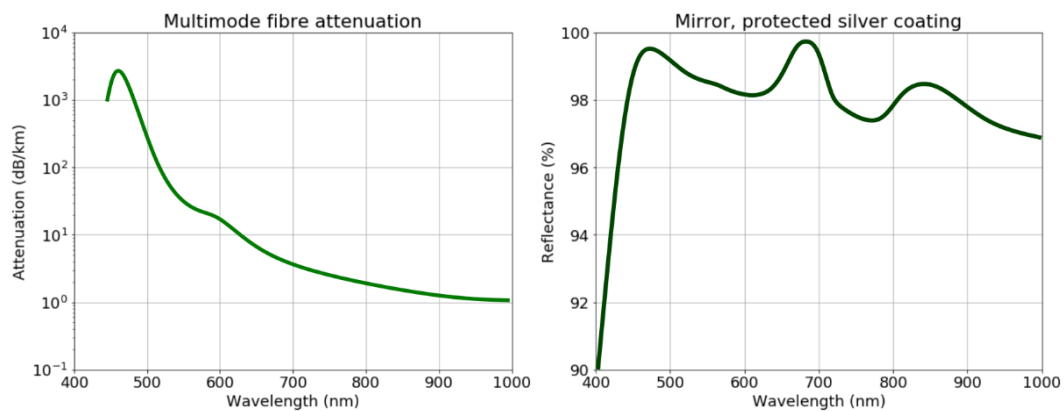

Figure 2 *Left: Attenuation in a standard optical fibre. Right: Reflectance of unpolarised light incident on a silver coated mirror. The reflectance is above 96% for most of the visible region.*

For most systems, the efficiency of the grating and QE of the detector will have the largest contributing factor to the final signal. Gratings are optimised for a specific wavelength (or blazed). Figure 3 shows the efficiency curve for a typical grating, blazed at 500 nm. Over a typical visible range of 400-850 nm there is a variation of almost 30%. It is therefore important to choose a suitable grating for your application. IS Instruments supply spectrometers with various blaze angles from 500-1000 nm to suit individual applications.
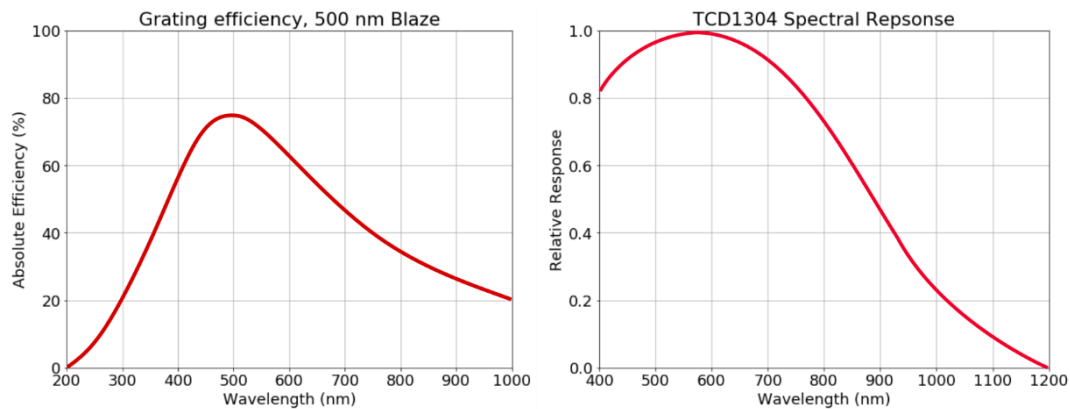
Figure 3 *Left: Diffraction grating efficiency for a typical grating. Right: Spectral response of the Toshiba TCD1304AP/DG CCD sensor (adapted from manufacturer datasheet).*

A silicon substrate is used for visible imaging detectors. Although silicon is well characterised, the exact form of the QE curve is different for every detector and a rough indication is usually provided in the manufacturer's datasheet.

3. Interference from detector cover glass

Detectors with cover glass can produce an interference effect. This effect is commonly referred to as window etaloning. Incoming light undergoes multiple reflections between the surface of the detector and the cover glass, as well as within the glass itself, which results in destructive and constructive interference. This is particularly pronounced in spectrometers because light incident on the detector is close to monochromatic. The effect is most obviously visible on broadband spectra as a low frequency oscillation or ripple in the signal.

For a detector with uncoated cover glass, three reflection scenarios are possible (plus the base case when all the light is captured). These are shown in Figure 4. (Novak et al., 1997) argue that the reflectance of the CCD is likely to be low enough that the majority of the interference is caused solely by the window. The effect is challenging to model numerically, so it is difficult to determine exactly which reflection scenario is causing the problem. Some interesting non peer-reviewed work investigating this phenomenon was performed by Peter Schlatter[1].
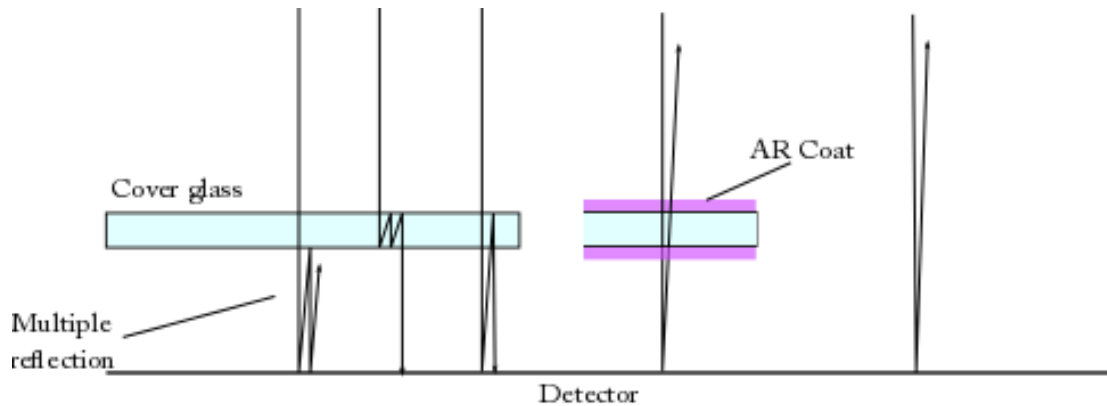
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[1] http://www.astrosurf.com/aras/fringing/schlatter/ripple.htm

Figure 4 *Reflections that occur inside a covered detector. The left image shows the usual case: light can reflect between the detector and glass. Middle: if a (double-sided) AR coating is used, most light that reflects off of the detector is lost. Right: If no cover glass is present, all the reflected light is lost.*

The periodicity and exact shape of the signal is dependent on several factors, including the distance between the cover glass and the detector, as well as their reflectance.

A similar effect is seen in back-illuminated NIR detectors, where the detector substrate itself acts as an optical etalon. Etaloning is an effect which occurs when light reflects between two flat surfaces, separated by a small distance comparable to the wavelength of the incident light. In back-thinned detectors, the optical thickness of the substrate is tens of microns which is 100-200 times the wavelength of the light. In the case of visible spectrometers, it is unlikely that true etaloning is occurring because both the cover glass thickness and the distance between the glass and detector are much longer than a wavelength.

Removing interference or 'etaloning' effects

Several options are available for preventing this problem: firstly, an AR coating could be applied to both sides of the detector window. This retains the advantage of having a protective cover over the CCD, but may only reduce fringing rather than eliminate it. Secondly, the window can be removed entirely. Finally, wedged cover class could be used. An optical wedge alters the refraction angle of light so that the incoming and outgoing rays are no longer parallel (and hence don't interfere). A comparison between window covered and windowless detectors used in IS-Instruments Mini spectrometers is shown in Figure 5.
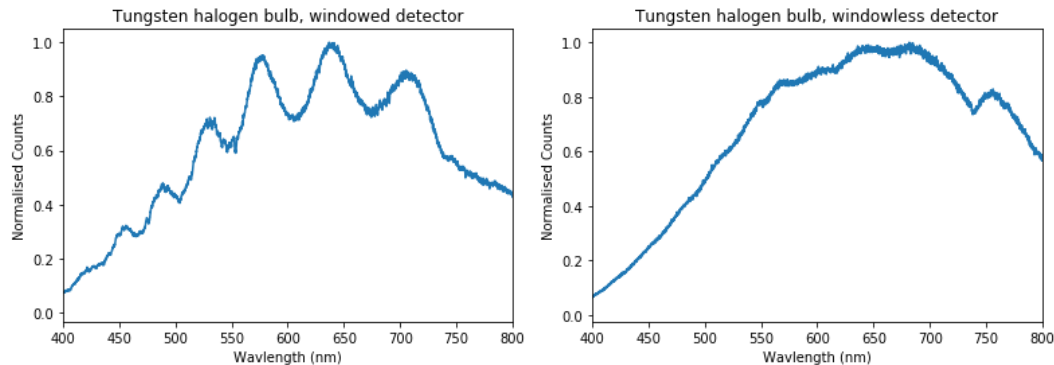
Figure 5 *(Left) spectrum of a tungsten halogen lamp, using a window covered detector (MSP1000 spectromter). Interference effects are clearly visible. (Right) spectrum of same lamp, using a windowless detector in the same spectrometer. No interference effects are present.*

Using a windowless CCD is the simplest and most cost-effective solution. The downside of this process is that removing the window exposes the detector to dust (after all, the purpose of the cover glass is primarily for protection). For spectrometers used in static environments, such as laboratories, this is unlikely to be a concern. If the spectrometer is used outdoors, in dusty environments or is moved frequently, it may be an issue.

For most users we recommend using a windowless detector for simplicity.

4. Correcting for instrument response

Full radiometric correction

The simplest way to compensate for the total spectral response of the system is to take the spectrum of a light source with a known emission. These lamps are provided with calibration data and can be used to perform radiometric correction of spectrometers. The procedure is essentially the same as a relative amendment, but with an additional scaling factor. Additionally, a radiometric calibration is only valid for the experimental setup where the rectification is performed. For instance, if a spectrometer is calibrated using a particular fibre, changing the fibre would void the result. For some spectrometers, even rotating the fibre should be avoided.

There are other issues to consider: a calibration lamp typically has a lifetime of less than 50 hours, before requiring a re-calibration. Lamps require a warm-up period that can be up to half an hour, even though acquiring the spectra may take milliseconds.

Calibration is dependent on accurate positioning of the lamp, and other instrument geometries (such as the aperture size for the spectrometer), all of which adds some uncertainty.
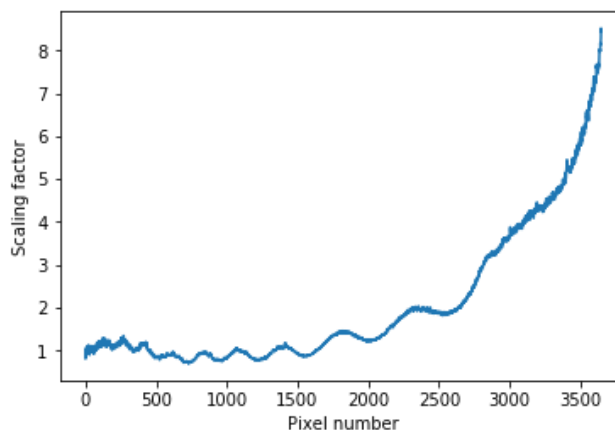
For these reasons, manufacturers typically do not provide radiometrically calibrated spectrometers as standard. However, there are some situations where this requirement is unavoidable.

Approximate relative correction

Approximation works reasonably well at removing instrument effects. A lamp with an emission spectrum close to a black body could be used – a common incandescent light bulb, for instance. These lamps contain tungsten filaments and produce light by resistive heating. Their emission spectrum can be calculated using the Planck relation:

$$I(v, T) = \frac{2hv^3}{c^2} \frac{1}{e^{\frac{hv}{kT}} - 1}$$

Where $I(v, T)$ at frequency v and temperature T. c is the speed of light, h is Planck's constant and k is the Boltzmann constant. This equation can be used to generate a theoretical blackbody spectrum for a lamp with a known temperature. The observed lamp spectrum is divided by this theoretical spectrum to give the relative instrument response. Each new spectrum is then multiplied by this response function. An example response function is shown in Figure 6. Note that the scaling factor is significantly increased at higher pixel numbers, corresponding to longer wavelengths where the detector is less sensitive.

Figure 6 *An example instrument response function generated using a household tungsten halogen lamp and a predicted blackbody spectrum. The sharp rise towards the right-hand side reflects that the CCD QE is poor in the infrared, so there is a larger correction here.*

The correction of this issue is discussed at length by many authors [2]. It should be noted that within [2], the authors describe that the calculated emission spectrum for a halogen lamp, with a known colour temperature, is shown to agree with the measured emission spectrum to within 5 %. Given that the accuracy of a traceable lamp is typically on the order of a few percent, this shows how accurate approximate corrections can be.

5. Summary

When performing spectral measurements, it is important to understand what calibration steps are required (if any). For relative measurements, it is not necessary to correct for the instrument response. However, if you require absolute measurements then you should perform either an approximate or full radiometric correction. If required, IS Instruments can provide spectrometers with windowless detectors to avoid common interference effects.

For more information about IS Instruments and our range of spectrometers, please take a look at our website.

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6. References

[1] Novak, E., Ai, C., Wyant, J.C., 1997. *Errors caused by nearly parallel optical elements in a laser Fizeau interferometer utilizing strictly coherent imaging*. Proc. SPIE **3134**, 456–460. doi:10.1117/12.295146

[2] Instrument Response Corrections, Technical Note 203, Horiba Jobin Yvon