Ocean Optics
Worldwide Headquarters
Largo, Florida, USA
+1 727-733-2447
info@oceanoptics.com

Sales, Service
& Support Facility
Duiven, The Netherlands
EU:
+31 26-319-0500
FR:
+33 442-386-588
info@oceanoptics.eu

Ocean Optics GmbH Sales,
Service & Support Facility
Ostfildern, Germany
+49 711-34-16-96-0
info@oceanoptics.eu

Sales Support
for the
United Kingdom
+44 1865-811118
info@oceanoptics.eu

Sales, Service
& Support Facilities
Shanghai, PRC – Beijing, PRC
+86 21-6295-6600
asiasales@oceanoptics.com

Glossary

Customers evaluating spectrometers are bombarded with spectroscopic terms and data, which can be overwhelming. To help you navigate this world, we've created this convenient glossary.

Spectroscopy products are sold with certain specifications that are rarely defined or include a methodology. That's why it's always worth asking, "How is that [specification] measured?" or "What do you mean that the spectrometer is good at this [performance parameter]?"

At Ocean Optics, we want to help our customers make informed decisions and to ensure that they receive the best information and support in the industry. As such, our goal with this glossary is to help filter out the hyperbole of competing performance claims and shed some light on definitions of frequently requested terms such as signal to noise ratio, thermal stability and sensitivity.

Have a term we have not explained? Submit it now!

Most Popular Terms: A-N

- Averaging
- Background Spectrum
- Chromaticity
- Data Transfer Speed
- Dynamic Range
- F-Number
- Linearity
- Noise
- Numerical Aperture

Most Popular Terms: O-Z

- Optical Resolution
- Quantum Efficiency
- Saturation
- Signal to Noise Ratio
- Slit
- Stray Light
- Thermal Stability
- Wavelength Range

A – B – C – D – E – F – G – H – I – J – K – L – M – N – O – P – Q – R – S – T – U – V – W – X – Y – Z

Aberration

An optical aberration is a departure of the performance of an optical system from the predictions of parallel axis optics. In a spectrometer, an optical aberration is typically seen when light from a single point does not converge back into a point after passing through the system and is seen as a "blur" or "smear" in the spectrum. Aberrations are not necessarily due to flaws in the optical elements, but occur because the simple paraxial theory is not a completely accurate model of the effect of an optical system on light. Different kinds of aberration that can affect an optical system include these:

- Chromatic aberration – different wavelengths are focused to different points by a lens, leading to fringe patterns in the spectrum.
- Coma – off-axis point sources are smeared out so they may appear with a tail.

- Astigmatism – light travelling in two perpendicular planes is focused at different distances by a lens, so part of an image may be in focus when another is blurred.
- Spherical aberration – light at the edge of a lens is focused more or less sharply than light at the center is focused, which leads to a sharp object becoming blurred around the edges.

It is possible to reduce the effects of some of these aberrations through the use of sophisticated optics and thin film coatings. Aberration can cause spectral peak shapes to be non-Gaussian for small slits and ultimately, limits a system's optical resolution when the entrance slit size is small.

Absolute (Spectral) Irradiance Calibration

Absolute irradiance calibrations require a lamp of known spectral power output to calibrate the spectrometer's response at each pixel. This modifies the shape and magnitude of the whole spectrum, correcting for the instrument's individual instrument response function. The modified spectrum is given in terms of power per area per wavelength, commonly expressed in units of **$\mu W/cm^2*nm$**. Please note that absolute irradiance is not the technically correct terminology for this quantity; as this quantity is wavelength dependent, the correct terminology should be absolute spectral irradiance.

Absorbance

Absorbance is measured in the dimensionless unit, AU. To understand how this relates to transmission, we must consider the Beer-Lambert (or Beer's) Law:

$$A = \varepsilon l c$$

where A is absorbance (in AU), **ε** is the absorptivity of the sample (i.e., how absorbent it is at a given wavelength, in $L*mol^{-1}*cm-1$), **l** is the path length of the sample (usually how wide the cuvette is, in cm), and c is the concentration of the sample (in $mol*L^{-1}$). The absorbance of a solution is therefore a useful quantity as it is directly proportional to the solution's concentration, **c**. At some concentration, this linearity starts to break down as less light is received by the spectrometer at the absorbent wavelengths and noise becomes more significant (a device with low noise will achieve a much higher maximum AU limit).

Beer's Law also states that the ratio of light intensity leaving a sample, I, to the incident light intensity on the sample, I_0 (commonly called transmittance, T), is given by the following equation (note that the absorptivity, ε, and the intensity, I, are wavelength dependent, so typically only the intensity of the peak absorbance wavelength and the sample's absorptivity at that wavelength are used in absorbance calculations):

$$T = I/I_0 \propto e^{-A} = e^{-\varepsilon l c}$$

As A is dimensionless, it is commonly scaled to give the following relation:

$$A = \log_{10} 1/T = \log_{10} I_0/I$$

Therefore, it can be seen that if a known sample solution is doubled in concentration, the absorbance, A, value will double, and the transmittance, T, will drop to 10% of the original value.

Note that as absorbance measurements scale up towards the upper-end of the achievable range for a given spectrometer configuration, it may be worth referring to this computed value ($\log_{10}(1/T)$) as ***uncorrected absorbance***. As you approach the stray-light limit of a bench, you will need to correct this value using a transform function generated from reference absorbance measurements of a known absorbance value (such as an OD5 filter). This curve will show that AU measurements can be quite accurate and linear for a certain range of OD, then need to be adjusted (generally downwards) above a stray-light threshold.

See also Absorbance in Measurement Techniques.

Analog Input/Output

The analog input/output pins allow the spectrometer to communicate with an external device. For example, the voltage on the output pin can be incrementally varied within a specified range to control an external device, so a lamp controlled by the analog output pin may change intensity based on the voltage produced by the spectrometer. In this situation, the lamp may be set to zero intensity at 0 V and maximum intensity at +5 V, with the brightness of the lamp varying gradually in 0.1 V increments. In return, the analog input pin can accept

changing voltage from an external device to alter some characteristic of the spectrometer system (such as the trigger delay). Unlike GPIO pins (which exist only as On or Off states), the analog input/output pins are incrementally variable.

Analog to Digital Converter (ADC)

This component in the spectrometer is responsible for converting the voltage from the detector into a digital signal that is sent to and processed by the computer for graphical display. The incident photons produce electrons in the detector pixels, which are then converted by the A/D into a digital signal. The speed at which the A/D sends data to the computer is measured in MHz (millions of cycles per second). Since the detector maximum clock speed is usually the limiting factor in the speed of the spectrometer system, A/D speed specifications should not normally be used to compare the capabilities of different spectrometers. Additionally, the speed of other electronics in the device can limit the overall throughput rate of the spectrometer. Speed or resolution of the analog to digital converter, therefore, is not a figure of merit for a spectrometer.

Autonulling

The autonulling feature available on certain spectrometers is designed to adjust the baseline offset of the spectrometer to a user defined level. This is useful when trying to use two different spectrometers to look at the same light source. Using autonulling, the baselines of the different spectrometers can be made to match each other.

Averaging (Time and Spatial)

When viewing or capturing a spectrum, two kinds of signal averaging are possible: time-based averaging and spatially based averaging.

Time-based averaging increases the amount of spectral information captured by calculating the average outputs of individual pixels over multiple spectral scans. This process takes more time than viewing the results of one scan but produces a higher signal to noise ratio (SNR) and stabilizes fluctuating data. The SNR will increase by the square root of the number of time-based averages. For example, if 100 averages are used, the SNR will increase by a factor of 10, but the measurement will take 100 times as long to acquire than a single scan.

Spatially based averaging (or boxcar smoothing in Ocean Optics software) will visually smooth the results of a single scan by averaging the values of adjacent pixels together. This process improves the SNR at the expense of optical resolution. Spatial averaging is useful when the spectrum is relatively flat and little variation is expected between adjacent pixels, as the resultant loss of resolution can make it difficult to distinguish sharp spectral features. When using spatial averaging, the SNR will increase by the square root of the number pixels averaged.

Background Spectrum

Background is the signal level that represents the expected output when no sample is present. This is distinct from a dark or dark spectrum, which represents the expected output when absolutely no light is present. This important distinction can be seen in the following example:

Consider a reflection measurement using a fiber guided light source but performed in ambient room lighting. In this case, even if a perfectly black sample is being measured, room light would enter the input fiber. Blocking the input fiber would block all light and fail to take this background light into account, resulting in a perfectly black sample still showing some reflection since the ambient room lighting would be interpreted as coming from the sample. When taking a background spectrum, only reference light should be prevented from entering the spectrometer; in this case, the fiber guided light source should be switched off when taking a background spectrum to account for the background lighting.

Bad Pixel

See Defective Pixel

Band Gap (also Bandgap)

In semiconductors, such as silicon detectors, the bandgap refers to the electron energy difference between the top of the valence band and the bottom of the conduction band. When a photon with energy that matches this bandgap lands on the detector, an electron is promoted from the valence to the conduction band and is added to the pixel "pool" for processing. The electronic is stored in the pixel well until the accumulated charge is removed from the detector and transferred to the A/D converter. The converter output is processed and forms the desired spectrum.

However, electrons also may be promoted due to heat. The detector has no means of distinguishing these electrons from those due to photon absorption. These unwanted electrons are responsible for dark noise. Since photon energy decreases as wavelength increases, infrared photons above 1100 nm are impossible to detect with a silicon CCD because they lack the necessary energy to promote an electron across the bandgap. Infrared spectrometers generally rely on InGaAs detectors because they have a smaller bandgap and a higher wavelength cutoff than silicon detectors. A side effect of the smaller bandgap is higher dark noise from "heat-promoted" electrons.

Baseline Drift

Baseline drift of a spectrometer is an overall deviation in the average baseline offset as a result of a temperature change. As temperature increases, the contribution of counts due to dark noise will increase. Depending on the detector, however, the electronic offset may increase or decrease as the temperature goes up.

The Sony ILX511B detector is an excellent example of how a temperature increase causes the baseline to drop because the negative electronic offset effect overshadows the slight increase due to dark noise. In theory, a temperature change could produce identical and opposing effects in a detector, thereby nullifying any baseline drift.

Baseline Noise

Baseline noise is the summation of readout noise, dark noise, and electronic noise. The baseline noise specification is measured by setting the spectrometer to its lowest integration time (to reduce dark noise to its lowest possible value), then removing all light from the spectrometer and recording 100 spectra. The mean value of the standard deviation for each individual pixel's output gives the minimum baseline noise of the device in raw counts. Baseline noise is not a figure of merit but is used in calculating dynamic range.

Baseline Offset

Baseline offset refers to the number of counts that the device reports when given no light. This value can be slightly different for each pixel on the detector. The resulting shape of this pixel to pixel offset difference contributes to fixed pattern noise. There are three basic contributors to baseline offset: electronic offset, dark current and readout noise. A single average value for a device can be calculated by averaging all the baseline offsets across the detector.

Bend Radius

The minimum radius of a circle the fiber can be bent into without risk of damage. This term can be little confusing because smaller numbers means tighter bends are allowed. This radius is a function of fiber diameter with larger fibers being stiffer and have larger minimum bend radius.

- LTBR (long term bend radius):Observe as a minimum radius allowed for storage conditions.
- STBR (short term bend radius):Observe as a minimum radius allowed during use and handling.

Read more about Bend Radius at our dedicated webpage.

Best Efficiency (of a diffraction grating)

All ruled or holographically etched gratings optimize first-order spectra at certain wavelength regions; the "best" or "most efficient" region is the range where efficiency is greater than 30%. In some cases, gratings have a greater spectral range than is efficiently diffracted. For example, the Ocean Optics Grating 1 has a 650 nm

spectral range, but is most efficient in the 375 nm range from 200 nm to 575 nm. In this case, wavelengths greater than 575 nm will have an apparently lower intensity seen at the detector due to the grating's reduced efficiency.

Bidirectional Reflectance Distribution Function (BRDF)

A function that describes the ratio of radiance coming off of a surface to irradiance onto the surface for specified output and input directions Since the input and output direction are each 2-dimensional (azimuth angle and zenith angle), the complete function is 4-dimensional. Because normal BRDF does not include wavelength terms it is not very useful for spectroscopy and not a good model for most surfaces. Adding an incident wavelength term easily fixes this. However, the full BRDF requires a goniometer setup, and most of the time the full wavelength-dependent BRDF is not necessary — a simple subset or approximation is adequate.

For example, a surface is frequently only characterized by its diffuse reflectance (45° input angle, 0° output angle) and specular reflectance (0° input angle and 0° output angle).

Blaze Wavelength (of a diffraction grating)

For ruled gratings, the blaze wavelength is the peak wavelength in an efficiency curve. The slope of the triangular groove in a ruled grating is typically adjusted to enhance the brightness of a particular diffraction order at a particular wavelength. Holographic gratings have sinusoidal grooves and so are not as bright, but have lower scattered light levels than ruled gratings and therefore reduce stray light. For holographic gratings, there is no blaze wavelength.

Blue Light Hazard

Currently the subject of much research and debate, this term describes possible damage to the retina caused by wavelengths within the visible spectrum, specifically from the 400-500 nm range, as opposed to UV wavelengths, which are known to cause damage. Particularly strong damage is believed to result from exposure to light below 430 nm. Spectrometers can provide detailed data at all wavelength of interest for a light source, instead of lumping the whole spectrum into simple xy chromaticity.

Boxcar Smoothing

Boxcar smoothing is a type of spatial averaging that may be applied to a spectrum. This processing removes noise by averaging the values of adjacent pixels and therefore improves the signal to noise ratio at the expense of optical resolution. Spatial averaging is useful when the spectrum is relatively flat and little variation is expected between adjacent pixels, as the resultant loss of resolution can make it difficult to distinguish sharp spectral features. When using spatial averaging, the SNR will increase by the square root of the number of pixels averaged. Please note that in Ocean Optics software, the value entered for boxcar width is the number of pixels to the left and to the right of the individual pixel that are averaged together. A boxcar smoothing value of 4 actually averages 9 pixels together (4 to the left + 1 center pixel + 4 to the right) and boosts SNR by a factor of 3. Similarly, a boxcar smoothing of 2 (5 pixels) would boost SNR by a factor of 2.2, and a boxcar of 0 (1 pixel) boosts SNR by a factor of 1 (thereby leaving the spectrum unchanged).

As most spectrometers "oversample" the spectrum (that is, the optical resolution exceeds the distance between two pixels on the detector), one can average the signal from several neighboring pixels to decrease noise without losing spectral resolution. In OceanView this type of noise reduction is performed through boxcar averaging. The number of pixels included in the average on either side of the center pixel is selected with the "Boxcar width" setting, with zero corresponding to no averaging.

However, once the total number of pixels included in the average exceeds the pixel resolution of the spectrometer, one starts to trade off smoothing against spectral resolution. The pixel resolution of the spectrometer is dependent on the spectrometer bench and slit size (read How does my choice of spectrometer slit size affect optical resolution?) For a Flame-S spectrometer with a 10 µm slit, for example, a boxcar width of 2 or more will begin to degrade the resolution of the spectrometer. This is often not an issue, but should be considered for applications requiring high resolution, or in which there are sharp features prone to detector saturation, like the D-alpha line observed in a deuterium lamp spectrum.

CCD Back Thinned Detector

The front side of a traditional silicon CCD detector contains several structures that are responsible for transferring electron charge out of the pixels. These structures reduce penetration of all wavelengths of photons to some extent. They greatly reduce photons below 450 nm and completely block photons below 400 nm, giving a standard silicon detector poor response in the ultraviolet wavelength range. A back thinned detector overcomes this UV absorption by shining the light in through the back side of a detector chip that has been thinned by etching. By entering through the back of the chip, the UV photons do not need to pass through these absorbing structures to be detected, making the chip significantly more sensitive in the ultraviolet range. However, the etching process is expensive and produces a chip that is significantly more fragile. Another method used to boost UV performance of a detector is through the application of an ultraviolet coating that fluoresces under UV light. This coating emits photons at lower frequencies that may be picked up by pixels at the UV end of the detector.

Charge-Coupled Device (CCD)

A charge-coupled device (CCD) is an electrical component responsible for converting incoming photons into an electric charge. The detector in a spectrometer is one example of a CCD that is used for measuring the amount of light entering the system at each wavelength. As photons land on different pixels of a CCD, electrons are generated and stored. After a sample has been recorded, the accumulated charge is transferred away from the chip, digitized and sent to the computer for analysis. The spectrometer output is shown as a spectrum.

Chromaticity

Using Ocean Optics spectrometers, the chromaticity, or color, of a sample may be measured. Chromaticity is a photometric parameter (matching the response of the human eye) and is typically given in CIE standard coordinates. The human eye contains cone cells that act as red, green and blue color sensors; every color that you “see” is a combination of the outputs of these cells. Similarly, a spectrometer calculates the color of a sample by approximating the photometric responses of these sensors (based on its spectral output) to most closely match what we see. The spectrometer can go a few steps further by quantifying the sample colors seen and calculating the following parameters:

- Correlated Color Temperature (CCT) – this is the temperature of a black-body radiation source that emits light of a color that most closely matches the sample’s color. Confusingly, a light source can be described as cool if it bluish or warm if it is more red in color, whereas black bodies change from red to yellow to white to blue on increasing temperature. A blue LED with a very high CCT may be described as looking “cooler” than a red LED with a much lower CCT.
- Color Saturation – this is a measure of how rich the color of the sample is. Whiter samples, nearer the middle of the chromaticity plot below, are less “color saturated” than those that appear nearer the edge of the plot. This term is not to be confused with Saturation.
- Dominant Wavelength – this is the wavelength at which a line projected from the white “center-point” in a CIE color diagram through the sample CIE coordinates hits the edge of the plot. This is not necessarily the wavelength of the highest peak in the spectrum.

Chromaticity is usually illustrated with the diagram below, which contains every color hue perceivable with the human eye. Around the edge of the plot (moving clockwise from the bottom corner) is increasing visible wavelength. Every color seen can be generated by mixing the colors of wavelengths around the edge of the plot. Samples are typically given CIE xyz coordinates (as seen in the x-y plot here), although others such as L*a*b* are commonly used.
The perceived color of a sample will vary with incident light, so it is important to state what you are illuminating your sample with when performing color reflection measurements.

CMOS Detector

A CMOS (complementary metal-oxide-semiconductor) detector performs the same function as a CCD detector, converting incident photons into an electric charge. CMOS detectors are a newer technology than CCDs, the driving force of which is smartphone cameras.

Each CMOS detector pixel has an amplifier attached that transfers the accumulated charge after a measurement has been made to the A/D converter (whereas a CCD will transfer each pixel's charge individually to a single amplifier). CMOS detectors may contain more fixed pattern noise compared with a CCD and individual linearity corrections will be needed for each pixel. CMOS detectors do have a reduced charge leakage from one pixel to its neighbors, improving sharpness of peaks. CMOS detectors can typically operate at much higher speeds than CCDs.

Collimated

Light entering a sample or spectrometer may be characterized as collimated or diffuse. Collimated light contains only light beams that are parallel, whereas diffuse light contains light beams in a number of directions.

For certain techniques, such as absorbance measurements, collimated light must enter a sample, then pass through it, and be captured by the spectrometer at the other side. To ensure that this is the case with Ocean Optics spectrometers, collimating lenses must be attached to the fiber from the light source and the fiber to the spectrometer.

Communication Bus

The communication bus is the port through which the spectrometer transfers data to the computer. Ocean Optics spectrometers utilize USB, RS-232, SPI, I^2C or Ethernet to link with the computer.

Cosine Corrector

A cosine corrector is an optical diffuser that captures a light signal from a 180o field of view. These are typically coupled to an optical fibre, or in some cases, directly to the aperture of a spectrometer. These are ideal for measuring irradiance from a plane surface.

Dark Current

Dark current is the result of random thermal fluctuations producing enough energy to promote an electron across the band gap, creating an electron-hole pair. The electron-hole pair is separated by local electric fields and the free electron is stored in the well. The spectrometer has no means to differentiate these thermal electrons from those generated by incident photons, and they therefore appear as noise in the spectrum. The generation rate of electron-hole pairs at a given temperature is referred to as dark current. The fluctuation in dark current is a result of shot noise and gives rise to dark noise. Since dark current is a continuous production of electron-hole pairs, longer integration times result in higher numbers of electrons generated by dark current. Thermoelectric cooling of the CCD reduces the dark current and dark noise dramatically, and in practice, high performance spectrometers are usually cooled to a temperature at which dark current is negligible over a typical exposure interval.

Dark Noise

Dark noise arises from the statistical variation in the number of thermally generated electron-hole pairs generated within the silicon structure of the CCD. Dark noise is independent of photon generated signal but is highly dependent on device temperature. The generation rate of electrons at a given CCD temperature is referred to as dark current. Dark noise is a form of shot noise and follows a direct relationship to dark current, and is equivalent to the square-root of the number of electrons generated within the integration time. Thermoelectric cooling of the CCD can dramatically reduce dark current and dark noise. In spectrometers where photon energy is extremely low and dark noise can easily drown out useful signal, thermoelectric cooling can reduce dark current to negligible levels over the exposure interval.

Dark Spectrum

A dark spectrum is the set of counts versus wavelength values for a spectrometer at a given integration time when no light is present (either from the sample or from ambient environmental light sources). This spectrum is used to correct for baseline offset and fixed pattern noise. The dark spectrum is also referred to as "dark signal" in other Ocean Optics literature. Note that this is different from a Background Spectrum, which represents the spectrometer signal in the absence of reference light.

Data Transfer Speed

Data transfer speed is the number of spectra per second that the device can acquire and transfer (assuming no latency created by the receiving device). This number will usually be communication bus dependent. Maximum data transfer speed cannot be calculated simply by **1/minimum integration time** as there are other sources of latency beside the integration period.

Dead Pixel

A pixel or group of pixels that shows considerably less response than the average surrounding pixels. Sometimes also called a drop out. If the pixel is simply weak and not totally dead, it can be considered as part of the instrument response function and corrected with proper referencing. However, the lower responsiveness of the pixel will result is a lower SNR for that pixel but this is usually not a problem. If the pixel is too weak or totally unresponsive, it can be treated as a defective pixel and interpolated.

Defective Pixel

A pixel that has unacceptable behavior. This behavior could be that it is a dead pixel, a popping pixel or an unacceptably hot pixel. The typical solution is to not use the pixel and replace it with an interpolated value. The STS, NIRQuest series, and educational models support storage of the locations of pixels for reference. Omnidriver and OceanView will automatically replace pixels with the average of adjacent good pixel before and after the pixel.

Detector

The detector in a spectrometer captures light and outputs an electrical signal. Ocean Optics spectrometers are CCD or CMOS detectors, typically made from Silicon (in the case of UV-VIS measurements) or Indium-Gallium-Arsenide (in the case of NIR).

These semiconducting materials accumulate a charge due to the photon-liberated electrons, which is then read out at the end of each reading. This read out value is processed for each pixel, and a spectrum is calculated.

Diffraction Grating (also known as Grating)

In optics, a diffraction grating is an optical component with a periodic structure that splits and diffracts light into several beams traveling in different directions. The directions of these beams depend on the spacing of the grating and (most importantly for spectroscopy) the wavelength of the light. In a spectrometer, the grating acts as the dispersive element.

Most spectrometers make use of a grating to split the incoming beam of light into its component wavelengths. This makes use of the optical principle of diffraction; that different wavelengths will be transmitted or reflected from a dispersive element through varying angles, thereby separating one multi-wavelength beam into many single-wavelength beams.

Ocean Optics provides a range of diffraction gratings to account for a variety of wavelength ranges and resolutions. Typically a balance must be struck between these two parameters: as you increase the number of lines/mm on a grating, you increase resolution but decrease the wavelength range that may be scattered.

Diffuse

Light entering a sample or spectrometer may be characterized as diffuse or collimated. Diffuse light contains light beams in a number of directions, whereas collimated light contains only light beams that are parallel.

To make free-space measurements, an Ocean Optics diffuser accessory may be attached to the spectrometer. This will capture light within a 180º field of view. These diffusers may also be used to capture spectral emissions from a plane.

Dispersion (concept)

Dispersion is the wavelength-dependent separation of light. In a spectrometer, separation of light can be caused by a prism or by a diffraction grating. It is this dispersion of light that allows different wavelengths to hit different pixels on the detector.

Dispersion (value)

The ratio of spectral range of a diffraction grating to the number of detector elements is called dispersion. This value is measured in units of **nm/pixel** and, alongside the pixel resolution, is useful in determining the optical resolution of a spectrometer. Please note that Ocean Optics uses a slightly different definition for dispersion than the commonly used units for a diffraction grating.

Drop out Pixel

One or more dead or weak pixels.

Dynamic Range (Single Acquisition/System)

Dynamic range is the maximum detectable signal (seen at near saturation) divided by the minimum detectable signal – it can be thought of as the number of different intensity elements that may be resolved by a spectrometer. The minimum detectable signal is defined as a signal whose average is equal to the baseline noise. This represents a signal to noise ratio of 1.

The dynamic range specification for a single acquisition is reported at the shortest integration time giving the highest possible dynamic range. The dynamic range specification of the system as a whole is defined as the product of the ratio of maximum to minimum signal at the longest integration time and the ratio of the maximum to minimum integration time.

$DR_{single\ acquisition}$ = number of counts at saturation/baseline noise at shortest integration time

DR_{sys} = (number of counts at saturation/baseline noise at longest integration) x (longest integration time/shortest integration time)

Electric Dark Correction

In order to compensate for changes in baseline offset over time, certain Ocean Optics spectrometers have a group of pixels that are optically masked to prevent light from reaching them. The output values these dark pixels generate are averaged and then subtracted from the values reported by all of the pixels in the detector when Electric Dark Correction is enabled. This drops the baseline offset reading (no light) of the detector to near zero counts for all pixels and more importantly, automatically compensates for any changes in baseline offset that may occur during an experiment. Use of electric dark correction is highly recommended.

Electronic Noise

One component of electronic noise is noise that is created in the signal path to the A/D converter. This can be a result of noise coupled in from other electronics in the device, amplifier noise, or as a result of errors in A/D conversion. Conversions of exactly the same charge will not necessarily yield exactly the same result from the A/D. Quantization error will also appear in the electronic noise.

Electronic Offset

Electronic offset is the number of counts displayed when the detector puts out its lowest possible voltage. This is the result of how the detector output voltage is mapped to the A/D converter input voltage range. This number is independent of dark noise, readout noise, electronic noise and useful signal photons. Electronic offset can be temperature dependent and in some devices may cause the baseline offset to drop as temperature increases, instead of increasing as one might expect from a typical CCD. The HR2000+ and USB2000+ spectrometers display this phenomenon. At short integration times, most of the baseline offset value is a result of the electronic offset. Baseline noise adds to this value to inflate the number of counts displayed on the graph when no light is present.

F-number

The f-number is a ratio of an optical component's diameter to its focal length and is related to numerical aperture. The collimating mirrors in many of Ocean Optics spectrometers, for example, are ƒ/4 (sometimes written as ƒ:4 or ƒ-4). This means that the focal length is four times the diameter of the mirror. An optical

component with a smaller f-number is better able to gather light but is more susceptible to the effects of aberration than a component with a larger f-number. In any compound optical system the effective f-number is dictated by the optic with the largest f-number.

Field-Programmable Gate Array (FPGA)

A field-programmable gate array (FPGA) is the logic chip that contains the program code necessary to run certain Ocean Optics spectrometers. Unlike pre-printed circuit boards, FPGAs can be rewritten to make changes when firmware updates are necessary.

Figures of Merit

“Figures of merit” is a generic term not specific to spectroscopy. It refers to the specifications that are most useful for comparing the utility of a device or system. It is important to clearly identify the true figures of merit in any system and ignore other irrelevant specifications that do not directly indicate final performance. When evaluating a spectrometer, these are the key figures of merit:

- Dynamic Range
- Optical Resolution
- Signal to Noise Ratio
- Sensitivity
- Stray Light
- Wavelength Range
- Thermal Stability

Firmware

The firmware is the program code that is permanently stored on the spectrometer’s memory chip. Firmware instructs the spectrometer on how to run all of the electronics in the spectrometer and allows the device to interface with the user’s computer. Firmware also retains certain operating parameters that govern the performance of the spectrometer (like wavelength calibration coefficients).

Fixed Pattern Noise

Each pixel acts as a separate detector and may have a slightly different baseline offset and sensitivity to its neighbors. The sensitivity difference is known as photo response non-uniformity (PRNU). This creates non-random structures on the data. Its effects can be compensated for in software by subtracting a dark spectrum and performing an irradiance calibration.

Fluorescence

Fluorescence is the absorption and subsequent emission of light of two different frequencies, or wavelengths. This is typically seen in experimental setups when a lower wavelength band of incident light is absorbed from one direction, and a higher wavelength band of light is emitted in all directions. This is most striking when a sample absorbs ultraviolet light (invisible to the human eye) and emits visible light.

A sample molecule may be excited electronically and vibrationally by an incoming photon, relax to a lower vibration state by heating up the sample around it, and then return to the electronic ground state by emitting a lower energy (higher wavelength) photon than the absorbed one.

Fluorescence can be used to investigate a number of samples, as fluorescent molecules will absorb a certain wavelength and emit another. With a known incident light wavelength, a sample may be identified by its fluorescent emission spectrum. As fluorescence occurs on a molecular scale (typically one photon in, one photon out), this is the only spectroscopic technique capable of identifying single molecules. See also Fluorescence in Measurement Techniques.

Fluorophore Coating

Fluorophore is a coating that can be applied to a detector to improve ultraviolet sensitivity. This coating emits photons at lower frequencies that may be picked up by pixels at the UV end of the detector. See Ultraviolet Coating.

Focal Length

The focal length of a lens or mirror is the distance from the optic at which incoming parallel light will converge to a single point in space.
The narrowness of the band of colors that a spectrometer can generate is directly related to the focal length of its collimating mirrors. A longer focal length in an optical system will result in higher optical resolution. However, using a longer focal length decreases the amount of light that can be accepted from the source since a longer focal length corresponds to a lower numerical aperture.

Full Width at Half Maximum (FWHM)

When analyzing spectral peaks on a graph, full width at half maximum (FWHM) is a useful way of characterizing the shape and overall value of a peak. FWHM is given as the wavelength difference between the two points on either side of the maximum at which the intensity is at half of the peak's maximum value. This provides not only a measure of a peak's height, but also its width. Similarly, the full width at quarter maximum (FWQM) may be used to characterize the spread of a peak.

General Purpose Input/Output (GPIO)

The general purpose input/output (GPIO) pins allow the spectrometer to communicate with external devices. These pins can be set as inputs to receive a digital signal from an external device or they can be set as outputs that deliver digital signals from the spectrometer to change the state of an external device. Unlike the analog input/output pins, the state of a GPIO pin is either on (+5 V) or off (0 V). The voltage cannot be incrementally varied within that range.

Groove Density (of a diffraction grating)

The groove density (mm^{-1}) of a grating determines its dispersion, while the angle of the groove determines the most efficient region and blaze wavelength of the spectrometer. The greater the groove density, the better the optical resolution possible, but the more truncated the spectral range. Groove density in mm^{-1} is sometimes written as lines per millimeter (l/mm) or grooves per millimeter (g/mm).

High Throughput Virtual Slit (HTVS)

Light exiting a fiber optic cable comes out in a circular cone described by the fiber's numerical aperture. As this light enters a traditional spectrometer, it must pass through an opening slit in the shape of a vertical rectangle. In order to completely fill the vertical dimension of the slit, much of the light on the left and right side of the slit is prevented from entering the spectrometer. For a narrow slit, this means a lower percentage of the light that leaves the fiber will actually make it to the detector. Despite its lower light throughput, a narrow slit is desirable because it offers higher optical resolution than a wider slit.

In order to achieve the best light throughput and resolution possible, an alternative design called a High Throughput Virtual Slit (HTVS) can be used. The circular shape of the light beam is chopped, manipulated and reassembled into a narrow, vertical rectangular shape using steering mirrors and lenses. This light is then split into component wavelengths as before and imaged by the detector. Therefore, light is not wasted, allowing for the same optical performance using significantly shorter integration times.

Hot Pixel

A pixel whose dark current is considerably higher than the average. The dark current for a hot pixel may also have a different temperature profile from the rest of the pixels. A hot pixel can generally be considered as part of the dark spectrum and can be correct by storing a background. As a result, a hot pixel is often not really a problem. An excessively hot pixel could be difficult to use if it saturates easily. In this case it is best to label it defective. A hot pixel will generally have higher dark noise associated with the higher dark current.

Instrument Response Function (IRF)

Every Ocean Optics spectrometer has what is called an instrument response function, or IRF. The IRF characterizes how the spectrometer responds to light across its wavelength range. This response is far from uniform: a spectrometer will produce a different response (here defined as the number of Quick View mode counts produced for a fixed number of photons) at every pixel. The IRF is non-uniform because of the cumulative effects of optical inefficiencies in the light path. These include, but are not limited to the following wavelength dependent effects: attenuation of light in the fiber optic cable; absorbance of light by the mirrors; grating efficiency; and detector response. The IRF for each spectrometer is unique, and cannot really be measured. However, it is possible to compensate for the IRF. The two common corrections are relative irradiance and absolute irradiance calculations.

Integration Time

Integration time is the length of time that the detector is allowed to collect photons before passing the accumulated charge to the A/D converter for processing. The minimum integration time is the shortest integration time the device supports and is dependent on how fast the detector can read out all of the pixel information. Integration time should not be confused with data transfer speed.

Jitter

When triggering an external device there is a certain amount of delay between when the signal is sent and when the device responds. This value, called latency, is consistent and can be accounted for. Jitter, on the other hand, is the uncertainty in the triggering delay. The triggering specifications for a spectrometer might be 8.3 µs ± 9 ns, for example. In this case, 8.3 µs is the trigger latency and 9 ns is the jitter. The lower the jitter value, the more reliably you can trigger external devices.

Lambertian Reflector

The perfect diffuser surface — i.e., having the same radiance output regardless of output angle. A Lambertian surface follows Lambert's cosine law, which states that the radiant intensity is proportional to the cosine of the viewing angle.

Latency

See Jitter.

Linearity

Linearity measures how consistently the spectrometer responds to light levels over its full intensity range. For example, if a 10 ms integration time of a stable source produces 500 counts, then a 100 ms integration time should produce 5,000 counts. A plot of counts per second versus integration time in an ideally linear device would be constant. The deviation from this straight line is a measure of nonlinearity. In order to correct for detector nonlinearity, an experiment is performed that looks at pixel response to a constant light source as integration times are changed. The data is then fit to a seventh degree polynomial and stored within the spectrometer to correct future measurements.

Linearity is not to be confused with absorbance linearity. The latter is the linearity stated in Beer's Law – a solution that absorbs light at a given wavelength will yield an absorbance peak at that wavelength, whose intensity will vary linearly with changing solution concentration. Therefore, if the concentration is doubled, the height of absorbance peak will also double. A spectrometer described as "linear up to 2.5 AU," for example, would show this relationship up to 2.5 AU, above which the relationship will break down (due to less incident light reaching the spectrometer making the signal noise more significant relative to the signal itself).

Noise

Noise is a general term for all unwanted signal in a spectrum. It can appear as a high-frequency, fuzzy series of lines that follows the contours of the desired spectral shape, a blurring of spectral peaks, or a low-frequency modulation of the spectrum. It is a combination of a number of different, often unrelated sources:

- Dark, or thermal, noise – caused by electrons that are thermally promoted in the detector rather than by incident light (increases with temperature, reduced by TEC)

- Photon noise – caused by statistical variation in the number of photons hitting the detector in a given time (shot noise) that increases with incident light intensity
- Electronic noise – errors made in the A/D converter and electronic circuitry that is misinterpreted by the spectrometer as a light signal
- Aberration – blurring/fringing caused by different focusing powers of the optical components at different wavelengths
- Stray light – light being scattered/reflected/refracted onto the wrong parts of the detector; this is an example of systematic noise
- Imperfections/defects in hardware – dead pixels or scratches in lenses may add/remove features in the final spectrum.
- Readout noise – noise resulting from reading a pixel's accumulated charge; this noise is introduced into the detector as a result of the read process itself and originates primarily from the detector's pre-amplifier

Typically, noise can be reduced by making use of spectral averaging and by controlling the temperature of the device.

Read the latest **Tech Tip: Noise in Spectrometers.** Download it now!

Noise Equivalent Power (NEP)

Noise equivalent power (NEP) is a way of relating the sensitivity of a detector to the overall performance of a spectrometer. NEP is the irradiant signal power required to produce a signal to noise ratio of 1 in an integration time of 0.5 s (this time is equivalent to a "1 Hz output bandwidth"). NEP is given in units of **W/√Hz**, and is determined using the following equation (where λ_p is the peak wavelength):

NEP (in W/√Hz) = noise spectral density (in A/√Hz) / responsivity at λ_p (in A/W)

The noise spectral density is the radiometric power of noise per unit bandwidth, and the responsivity is the current output per watt irradiated onto the detector (this is often referred to as the sensitivity of the detector).

The NEP of two systems may be used as a means of comparing their "sensitivity." For example, a spectrometer with an NEP of 0.001 W/√Hz can detect a radiometric signal power of 1 milliwatt at a SNR of 1 over a 0.5 s integration time, whereas a spectrometer with an NEP of 1 W/√Hz would only achieve a SNR of 1 in the same integration time when irradiated with an entire watt.

Numerical Aperture (NA)

The numerical aperture of an optical component (such as a lens or fiber) is a unitless quantity that characterizes the range of angles through which the component can emit or accept light. A fiber with a higher value for NA, for example, will have a larger acceptance cone for incident light. All Ocean Optics standard glass fiber optic cables have a numerical aperture of 0.22, which yields an acceptance angle of 12.7° in air. In any compound optical system the effective numerical aperture is dictated by the optic with the smallest numerical aperture. For lenses and mirrors, a number related to numerical aperture, called the f-number, can also be used to describe the light acceptance cone.

Read more about Numerical Aperture at our dedicated webpage.

Optical Density

This term is used to both refer to the absorbance of a sample and to the refractive index of a substance (the ratio of the speed of light passing through the substance to the speed of light in a vacuum).

Optical Resolution

Optical resolution of a spectrometer, measured as full width at half maximum (FWHM), depends on the groove density of the grating and the diameter of the entrance optics (optical fiber or slit). Resolution increases with an increase in the groove density of the grating, but at the expense of spectral range and signal strength.

Resolution also increases as the slit width or fiber diameter decreases, but at the expense of signal strength. Resolution is given by the following equation:

$$OR = SR/n \times PR$$

where,

OR = optical resolution of spectrometer (in nm)

SR = spectral range of grating (in nm)

n = number of detector elements (in pixels)

PR = pixel resolution for spectrometer and slit (in pixels)

The ratio is a value that Ocean Optics calls dispersion and is measured in nm/pixel. This is specific to the detector and grating combination.

Order Sorting Filters

Order sorting filters are applied to the detector's window and are designed to block second and third order diffraction effects. This prevents light of lower wavelengths from hitting the detector at a location designated for higher wavelengths. Without an order sorting filter, for example, light from the 253.652 nm line of a mercury source would appear at both the 253.652 nm and 507.304 nm spots on the detector.

PAR

Photosynthetically active radiation (PAR) is a measure of the amount of incident light that is absorbed by a plant and contributes towards photosynthesis. It is therefore a very useful parameter for those in the agriculture industry.

Photosynthesis is a quantum process: the number, not energy, of photons absorbed by chlorophyll determines the rate of chemical reaction (an absorbed 400nm photon will have the same photosynthetic impact as an absorbed 500nm photon with the excess energy given off as heat).

PAR is defined as the total number of photons landing in unit area in unit time, that have wavelengths within the range, 400nm – 700nm. Note that this method assumes all photons within this range have the same photosynthetic impact, and those outside it have none. Furthermore, it does not offer any indication as to the efficiency of absorption of each of these photons by the plant, only the amount of potentially "useful" light available. It is a "broadband quantity"; rather than a spectrum, a PAR reading will give a number calculated by adding up all the "useful" photons in the spectrum hitting a given point.

PAR units are typically given as $\mu mol.s^{-1}.m^{-2}$. The number of photons at each wavelength is calculated by dividing the *measured radiometric power* of the sample light at any wavelength by the *energy of a single photon* at that wavelength.

Photo Response Non-Uniformity (PRNU)

Photo response non-uniformity (PRNU) is the primary cause of fixed pattern noise in a spectrum. This is due to non-linear responses to incident light by individual pixels in the detector which, when exacerbated by a change in temperature or long integration times, may appear as significant variations in intensity between neighboring pixels. Fixed pattern noises may be removed by radiometrically calibrating the spectrometer.

Photometry

Photometry is the study and analysis of light as interpreted by the human eye. It is therefore a subset of radiometry. The brightness of different parts of the visible spectrum is modified to match the perceived brightness (response function) of the eye.

Photon Noise

Photon noise is a type of shot noise that results from the inherent statistical variation in the arrival rate of photons at the CCD. The interval between photon arrivals is governed by the Poisson distribution and therefore the photon noise is equivalent to the square root of the number of incoming photons. When the photon signal is small, the photon noise compared to the photon signal can be quite significant, driving the signal to noise ratio of the system down. Due to their different rates of increase, however, the noise becomes less significant

compared to the signal as the number of counts becomes very large. Even though the amount of photon noise is increasing as more light strikes the detector, the photon signal is growing at a much greater rate, causing the SNR to increase. It is important to note that, at small signal level, dark noise is the dominant source of noise, but at large signal levels, photon noise dominates. Frequently, the term “shot noise” is used in place of photon noise.

Pixel Resolution

The pixel resolution is the FWHM (as measured in pixels) produced by the slit image on the CCD. This number varies based on slit size and optical bench and is determined experimentally. This number, multiplied by the dispersion (in pixels), gives the optical resolution. In an ideal system, the plot of slit size versus pixel resolution would be a linear trend. However, aberration and finite pixel size limit pixel resolution when slit size is small. To assist customers with estimating expected resolution, Ocean Optics provides on our website tables of the pixel resolutions versus slit size for all of our spectrometer models.

Pixel Well Depth

The maximum number of electrons that each pixel in the detector can store is termed the well depth. The pixel well depth determines the maximum signal available for a single read-out event or acquisition. The dynamic range of a CCD is also directly proportional to the well depth. Incident light levels and integration time determine the number of electrons collected at each pixel. If the incident light generates more electrons than the pixel well can hold, the pixel becomes saturated. It is important to not allow the spectrometer to saturate (even in a part of the spectrum that is not being investigated) when taking a measurement as this may affect the rest of the spectrum.

Popping Pixel

A popping pixel is a pixel whose value changes suddenly. The pixel basically behaves like a hot pixel whose dark current will suddenly change magnitude. This can be particularity troubling because the suddenness of the value change means that even after referencing it can suddenly reappear in the processed spectrum. If a pixel I identified as a popping pixel it is best to treat is as a defective pixel and remove it. Popping pixels are largely unique to CCDs and are thought to be the result of charge traps caused by defects in the material.

Quantum Efficiency

Quantum efficiency is a measure of how well a detector generates electrons in response to incoming photons. A higher value for quantum efficiency means a more sensitive detector. Since the detector sensitivity changes for different wavelengths of photons, quantum efficiency is best expressed as a curve rather than a single value. For spectrometers, quantum efficiency is not a figure of merit since it is only one component in determining overall performance.

Quick View Mode

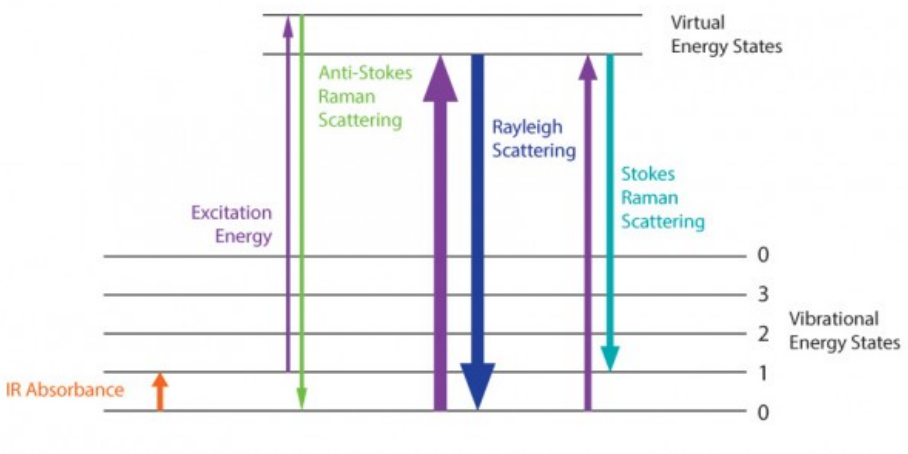
In Ocean Optics OceanView software, Quick View mode is the graph view that allows users to see raw detector counts without any adjustments, calibration or compensation. While Quick View mode is useful for setting integration time and adjusting light levels, it is not a truly accurate representation of the incoming light because it does not take into account instrument response function, fixed pattern noise and baseline offset. In order to view truly meaningful data for emissive measurements, the spectrum should be viewed using relative irradiance mode or absolute irradiance mode. Note that Quick View mode has replaced SpectraSuite’s Scope mode.

Radiometry

Radiometry is the scientific study of electromagnetic radiation, including the visible spectrum. It characterizes the power distribution of the electromagnetic spectrum, as opposed to photometry, which characterizes the perceived intensity of visible light as seen by of the human eye.

Raman

Raman spectroscopy is a method of finding a sample using a spectral fingerprint, as done with absorbance, fluorescence or transmission spectroscopy. The theory behind Raman is quite different, however, as is the experimental method of obtaining a Raman spectrum.



Raman spectroscopy makes use of inelastic scattering from a single-wavelength incident light beam in the visible or near-infrared spectrum. The sample absorbs the incident light beam as it is promoted to a virtual energy state before emitting it and dropping back to its original ground state – the excited states are deemed "virtual" as the sample molecules don't remain in that state for any time. Elastically scattered light will have the same wavelength as the incident light, whereas light scattered inelastically will be slightly higher or lower in wavelength. It is these differences in wavelength that can be used to identify the sample.

Inelastically scattered light is typically much lower in intensity to both the incident light beam and the elastically scattered light, and so the main difficulty in Raman spectroscopy is filtering out everything except the inelastically scattered light. Typically only one in a million incident photons will scatter inelastically. Using an Ocean Optics SERS substrate during the experiment may enhance the Raman signal of a particular sample.

The difference in wavelength between the elastic and inelastic scattering is due to a change in the sample's vibrational or rotational energy levels as a result of the absorption and near re-emission of the incident light beam. This is similar but ultimately different to the changes in energy level seen in infrared absorption/transmission spectroscopy, where the incident light is entirely absorbed at a corresponding wavelength.

Confusingly, the difference between the incident and inelastically scattered wavelengths is given in the unit, cm^{-1}, rather than nm, and so a spectrum for a sample will give intensity against cm^{-1}. Raman may be used for solid and liquid samples, is not destructive to the sample and may distinguish between molecular isomers. See also Raman under Measurement Techniques.

Readout Noise

Readout noise is the noise that results from reading a pixel's accumulated charge. This is noise introduced into the detector as a result of the read process itself and originates primarily from the detector's pre-amplifier.

Relative Irradiance

Relative irradiance uses a lamp with a known color temperature (but not necessarily known power output) to correct the shape of the spectrum but not the magnitude (hence its "relative" identifier). Relative irradiance allows the user to determine whether there is more light at one wavelength than another (which cannot be determined by looking at the raw number of counts due to the instrument response function), though it does not provide any information on how much power there is in absolute terms.

Saturation

Pixel saturation occurs when the incident light is large enough that the pixel well depth at a particular point has been exceeded and the detector generates the maximum possible voltage for that pixel. Saturation generally occurs as a result of exposure to an overly bright light source or as a result of an integration time that is too long. It is important to not allow the spectrometer to saturate (even in a part of the spectrum that is not being investigated) when taking a measurement as this may affect the rest of the spectrum.

Scope Mode

Scope mode has been replaced by Quick View mode in the OceanView software.

Second and Third Order Effects

When light is diffracted by the grating in the spectrometer, each wavelength splits into an infinite number of beams. The first, and most intense, of these diffraction beams for each wavelength is focused toward the detector. The second, third and higher beams are diffracted at higher angles. Because this diffraction is a cause of stray light, the inside of Ocean Optics spectrometers are painted with a black coating to minimize these higher order diffracted beams from reflecting off the inside of the spectrometer and landing back on the detector.

For wavelengths below half the maximum wavelength in the spectrometer's wavelength range, filters must be used to prevent 2^{nd} and 3^{rd} order beams from landing straight on the detector itself. A 250 nm component would be diffracted by the grating to land on the detector at 250 nm as well as at 500 nm and 750 nm. Similarly, a 350 nm component in the incident light would diffract onto the 350 nm and the 700 nm part of the detector. Therefore, a low-pass filter must cover the detector to stop 2^{nd} and 3^{rd} order diffracted beams from lower wavelengths giving false readings at twice or three times their actual wavelength.

Sensitivity

Sensitivity of a spectrometer is a measure of how the optical input (light) relates to the spectral output (counts) as seen in Ocean Optics software.

Detector sensitivity, not spectrometer sensitivity, is typically given in one of the following two ways:

1. Current output (Amperes, A) per incident radiometric power (Watts, W)

Sensitivity can be given in terms of the current produced by the detector for an irradiant light source of given radiometric power. The units for this are typically A/W (this is often referred to as a detector's responsivity, see NEP). When sensitivity is expressed in terms of A/W, the quantum efficiency of the detector and its sensitivity are directly related by the following equation:

$QE = Sx1240/\lambda \times 100$ (%), where λ is the wavelength in nm.

2. Voltage output (Volts, V) per incident photometric exposure (lux seconds, lux.s)

Sensitivity can also be given in terms of the voltage produced by the detector for a certain amount of photometric exposure. Common units for this method are V/lux.s.

Incident photons per count. The two definitions above are both difficult for spectrometer users to make sense of, as the detector output (in Volts or Amperes) is processed by firmware and software to give a spectrum. Instead, Ocean Optics specifications typically show the ratio of counts (as seen on the y-axis in OceanView or SpectraSuite) to the number of incident photons at a particular wavelength (typically given at 400 nm and 600 nm). This is the most useful definition as it relates directly to what a customer sees in Ocean Optics software.

A note of caution: "Sensitivity" is often used interchangeably with Noise Equivalent Power (NEP), which leads to confusion. Furthermore, when we describe a spectrometer being "sensitive enough to pick up very low light signals," this "sensitivity" is really determined by both the spectrometer's signal to noise ratio (SNR) and its incident photons per count ratio. Similarly, when we speak of a spectrometer's ability to pick out very small changes in a spectral peak, we should be clear that this "sensitivity" is determined by both its dynamic range and its incident photons per count ratio. The term "sensitivity" should either be clarified in these discussions.

Shot Noise

Shot noise is the statistical variation that is present in any discrete, random system. Types of shot noise relevant to spectrometers are photon noise and dark noise.

Shutter

A shutter is used to prevent light entering the spectrometer during dark measurements. It is typically controlled from the spectrometer as an external strobe so that it opens and closes in time with measurements. Shutters can be connected via optical fibres in front of the spectrometer, but the QE Pro contains an internal shutter to offer this control without the potential attenuation of signal along these fibres.

Signal to Noise Ratio

Signal to noise ratio (SNR) is defined as the signal intensity divided by the noise intensity at a particular signal level – it therefore may change measurement to measurement. Since the noise typically increases as a function of signal due to photon noise, the SNR function is actually a plot of individual SNR values versus the signal at which they were obtained. The value of a spectrometer's SNR reported by Ocean Optics in its datasheet is the maximum possible SNR value (obtained at detector saturation). The SNR response curve for each pixel is assumed to be the same.

The measurement is performed as follows: a light source is chosen so that the spectral peak just saturates at the lowest integration time or at an integration time well below the thermal noise limit (the spectrum should also have an area of low or nearly zero counts); to calculate SNR, take 100 scans without light and calculate the mean baseline count value at the each pixel, then take 100 scans with light and calculate the mean and standard deviation of each pixel output count; the signal to noise ratio is then given by the following equation:

$$\mathbf{SNR_\rho = (\overline{S} - \overline{D})/\sigma_\rho}$$

where,

SNR = signal to noise ratio

$\overline{S}$ = mean intensity of the samples (with light)

$\overline{D}$ = mean of dark (no light)

σ = standard deviation of samples (with light)

ρ = pixel number

To get the complete signal to noise ratio versus signal graph, plot the calculated SNR_ρ values (the noise) versus $\overline{S}_\rho - \overline{D}_\rho$ (the signal). This will cover a wide range of peak counts (from dark to nearly saturated). Since all of the pixels have the same response curve, the data for the SNR versus signal graph can come from all of the different pixels. Since photon noise is the largest noise contribution at large signal values, the ideal graph should have a shape that approximates $y = \sqrt{x}$.

Please note that signal to noise ratio can be improved by using different types of signal averaging. For time based averaging, the SNR will increase by the square root of the number of spectral scans used. A signal to noise ratio of 300:1, for example, will become 3000:1 if one hundred scans are averaged together. For spatially based averaging (boxcar), the SNR will increase by the square root of the number of pixels averaged together.

While these methods are useful for obtaining precise data, it can make it confusing to compare different spectrometers. Ocean Optics reports all of its SNR values without relying on the increase brought on by signal averaging. Many of our competitors take advantage of signal averaging to artificially inflate SNR values on inferior spectrometers.

Slit

The slit is the small opening that allows light to enter the spectrometer. The slit width is inversely related to the optical resolution of the spectrometer such that smaller slit widths will produce greater resolution. A smaller slit, however, allows less light into the spectrometer. For most Ocean Optics spectrometers, the slit height is 1000 µm and only the width varies (from 5 µm up to 200 µm). For spectrometers with no slit, the diameter of the optical fiber limits the amount of light entering the system and performs the function of the slit. Ocean Optic's Apex spectrometer uses a special design called a High Throughput Virtual Slit to overcome the trade-off between slit size and throughput.

Solid-state optical component

This component is at the heart of Ocean Optics' new device, the Spark. Rather than using a diffraction grating, a spectral sensor uses a solid-state optical component – a new technology developed by Ocean Optics – to split the sample beam. It is, therefore, a dispersive element that may yield a spectrum from a sample light beam.

It contains no moving parts, and no diffraction volume, and is therefore thermally stable. The design of this component is proprietary, and has allowed Ocean Optics to design the smallest spectral device currently on the market.

Spectral sensor

Spectral sensors are the latest addition to the Ocean Optics product range. They are tiny spectral devices, with their own range of accessories. The first product released in this range is the Spark-VIS.

Spectral sensors are designed for mass manufacture, low cost and tiny footprints. Ocean Optics first spectral sensor, the Spark-VIS, is our lowest cost spectral device, and the stripped back DET version is the smallest spectral device on the market – weighing under 1g!

A spectral sensor differs from a spectrometer in how it goes about obtaining the spectrum. Rather than using a diffraction grating, a spectral sensor uses a solid-state optical component – a new technology developed by Ocean Optics – to split the sample beam. The spectra obtained from these devices are used to identify and quantify samples.

Spectrometer

Ocean Optics manufactures miniature spectrometers and supplementary accessories. These devices analyse light by breaking down sample light beams into their constituent wavelengths.

The spectrometer sends this information to be processed, and a spectrum may be obtained for each sample. This spectrum highlights the relative signal at each wavelength and, by comparing a sample spectrum with a known (or reference) spectrum, valuable information may be obtained.

Ocean Optics' miniature spectrometers capture a beam of light through an aperture; they then use a diffraction grating to split this beam into its component wavelengths. The amount of infrared, red, green, blue, violet and UV (and everything in between) in the beam may be quantified and processed.

Light interacts with matter; some is absorbed, some transmitted, some scattered. By analysing the light passing through or reflecting off a sample, the sample may be identified and understood.

Ocean Optics spectrometers may be used as a component in a modular setup, allowing the user to work with a vast range of samples in an even wider range of applications and environments.

Spectrum

This is a graph showing how light from a sample source varies with wavelength. A spectrum is a 2-D graph, showing wavelength (typically measured in nanometres, nm) against some measure of intensity (depending on the experiment, this could be as a percentage, %, a power output, $\mu W.cm^{-2}.nm^{-1}$, or some arbitrary unit, counts).

Light interacts with matter; some is absorbed, some transmitted, some scattered. By analysing the light passing through or reflecting off a sample, the sample may be identified and understood.

Spectral devices, such as spectrometers, can obtain a spectrum by analysing light emitting from, passing through or reflecting off a sample. A spectrum may be unique to a sample, thereby allowing samples, and components within samples, to be identified and quantified. Spectroscopy can be used in all manner of environments – Ocean Optics modular spectrometers have brought the power of spectroscopy out of the lab and into the real world.

Spectral Range (of a diffraction grating)

The spectral range of a diffraction grating is the dispersion of the grating across the detector's linear array; also expressed as the "size" of the spectra on the array. The spectral range is a function of the groove density and detector size and does not change. When you choose a minimum wavelength for a spectrometer, you add its spectral range to this wavelength to determine the maximum wavelength. For several gratings, however, the spectral range of a grating varies according to the starting wavelength, so the higher the starting wavelength, the more truncated the spectral range.

Stray Light

Stray light is light that unintentionally lands on any part of the detector and gives a false reading. The detector may not distinguish between wavelengths landing on a pixel, it simply measures the intensity of incident light; therefore, if light lands on the detector at a wavelength where it shouldn't, the detector will erroneously output a reading at that wavelength. This stray light is typically from the intended source but scatters within the spectrometer and lands on the wrong part of the detector, but it may also be from a different source entirely.

This light will often set a working limit on the dynamic range of the system and it reduces the signal to noise ratio by limiting how dark the system can be. Absolute values for color or absorbance will be affected by stray light. Here are some common sources of stray light:

- 2^{nd} and 3^{rd} order diffraction
- diffraction grating defects
- internal reflection within the spectrometer
- leaks in the spectrometer casing

Thermal Stability

Thermal stability of a spectrometer is a measure of how spectral response varies as a function of ambient temperature. Due to thermal expansion and contraction of the spectrometer's metal housing and glass optics, wavelength peaks will drift slightly as the temperature increases or decreases. A low value for thermal stability means that wavelength drift will not be as extreme for a given temperature change. Thermal stability is expressed in units of nm/°C or pixels/°C. Dark noise is also a function of ambient temperature and may be reduced using Thermoelectric Cooling (TEC).

Thermoelectric Cooling (TEC)

In spectrometers where low noise is essential, a thermoelectric cooler (TEC) is employed at the detector. The TEC cools the detector to reduce dark current and dark noise generated as a result of ambient heat. Reducing this noise results in a more stable reading and is extremely useful in situations where the photon energy is very low, such as in infrared measurement. In general, high performance CCD sensors exhibit a one-half reduction in dark current for every 5 °C to 9 °C as they are cooled below room temperature. This rate of improvement typically continues to a temperature of approximately 5 °C to 10 °C below zero, beyond which the reduction in dark current diminishes quickly.

Triggering

Triggering is a feature that is available on many Ocean Optics spectrometers and involves one of two different processes. In the first type of triggering, an event outside the sampling system (such as a push button or laser pulse) changes the voltage level on the spectrometer's trigger pin that, in turn, instructs the spectrometer to begin spectra acquisition. This is referred to as "External Triggering" in Ocean Optics literature. In the second type of triggering, the spectrometer instructs an external device (such as a lamp) to illuminate immediately prior to spectral acquisition. This is referred to as "Triggering an External Event".

Below are five examples of triggering modes available on Ocean Optics spectrometers:

1. Triggering Modes, External Hardware Edge Trigger

The integration time is set by the spectrometer. The spectrometer waits for a sharp rise in voltage on the trigger input pin, and then acquires spectra. This trigger acquires one spectrum each time that there is a sharp rising edge (if an acquisition is not already in progress). Use this trigger mode when you are using a pulsed excitation source or light source in your experiment (such as a laser or flash lamp), when you are doing laser-induced fluorescence (fluorescence with pulsed excitation) or phosphorescence experiments, or when you need to synchronize an acquisition with an external event.

2. Triggering Modes, External Hardware Level Trigger

The integration time is set by the spectrometer. The spectrometer waits for a sharp rise in voltage on the trigger input pin, and then acquires spectra until the voltage is removed. Use this trigger mode when you need a continuous acquisition whenever a certain condition is met, such as when reacting to a sample being present or when a sample reaches a specific state that you want to measure.

3. Triggering Modes, External Software Trigger

The integration time is set in the software. The software receives a trigger event and transmits spectra obtained in the data acquisition cycle in which the trigger occurred. Use this trigger mode when you are using a continuous illumination source and the light intensity is constant before, during, and after the trigger.

4. Triggering Modes, External Synchronous Trigger

The spectrometer acquires data from an external trigger event (such as a push button) until the next time the trigger is activated, at which time the spectrometer ceases spectral acquisition and begins a new acquisition. Integration time cannot be set, since the trigger can fire at random intervals. Use this trigger mode when you must synchronize your scans to an external clock source, when you are using a lock-in amplifier, or when you are using a chopper.

5. Triggering Modes, Normal/Free Run/Continuous

The spectrometer continuously acquires spectra. Use this trigger mode when no synchronization to other events is needed.

Ultraviolet Coating

In a silicon CCD detector, quantum efficiency decreases significantly below 450 nm and is reduced to nearly zero for wavelengths below 400 nm. For spectrometers designed to respond in the ultraviolet range, the low wavelength portion of the detector is coated with a material designed to boost UV performance. This material, called a fluorophore, undergoes fluorescence and emits visible light photons in response to ultraviolet light exposure on pixels at the UV end of the detector. Since the detector is highly sensitive to photons in the visible range, the emitted photons are captured immediately by the detector and are interpreted as ultraviolet light by the software. Ocean Optics uses a UV coating that will not degrade significantly over time. Another method used to boost UV performance of a spectrometer is by using a back thinned detector.

Voltage Offset

The voltage offset is the voltage that the detector produces in response to zero incident photons. This is a function of the electronics on the detector and within the analog chain circuitry.

Wavelength Range

The wavelength range of a spectrometer is the range of wavelengths over which the device effectively captures and processes incident light. It is dependent on both the wavelength range of the detector and the spectral range of the diffraction grating.