Goniophotometry versus Goniospectroradiometry

A Technical Note by
Robert Yeo,
Technical Director,
Pro-Lite Technology Ltd

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Abstract

In recent years, the goniometer based upon a spectrometer (the "goniospectroradiometer") has become a popular choice for measuring the output of luminaires and for creating photometric data files in .IES and .LDT formats. This popularity is often attributed to the ability of a goniospectroradiometer to perform all of the relevant optical tests in one measurement (photometric, colorimetric and spectral). However, compared with the more traditional type of goniometric instrument based upon a filtered photometer (the "goniophotometer"), gonio-spectroradiometers suffer from a number of limitations arising from their relative lack of photometric sensitivity and more restricted dynamic range. This paper will explain why the traditional goniophotometer remains the preferred choice, based upon accuracy, ease of use and cost.

Introduction

Anyone involved in developing, manufacturing or supplying luminaires and light fittings will be familiar with so-called "photometric data files". A photometric data file is a computer-readable data file that details the performance of the lighting product in a standardised form. The two most common file formats are .IES (as defined by the Illuminating Engineering Society of North America, IESNA) or the .LDT (commonly referred to as "EULUMDAT", an industry-defined format that is popular in Europe).

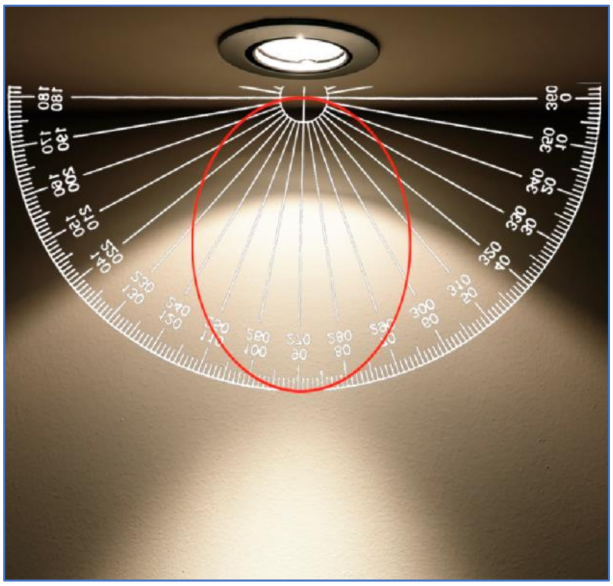

Figure 1: A photometric data file describes the shape of the beam and the distribution of luminous intensity (candelas) from a light source as a function of angle.

Photometric files in either .LDT or .IES formats are routinely used to model lighting schemes using lighting design software (e.g. RELUX, DIALUX). This simplifies the design of lighting in commercial, residential and industrial settings, allowing the lighting designer to define the number and placement of ceiling fixtures to achieve the desired level and uniformity of illumination without recourse to physical models.

Regardless of whether your file format of choice is .IES or .LDT (and files can be converted between formats with ease), the data file contains a table of luminous intensity values from the luminaire recorded as a function of angle of elevation and of rotation from the zero degree datum. Luminous intensity is the amount of luminous flux (units of lumens) that shines in a given direction from the light source per unit of solid angle (units of steradians) – see Figure 2. Thus, luminous intensity is reported in lumens per steradian, which is simplified to the more familiar unit called the candela. A lamp with an output of 1 candela emits a luminous intensity in a given direction equal to 1 lumen per steradian.

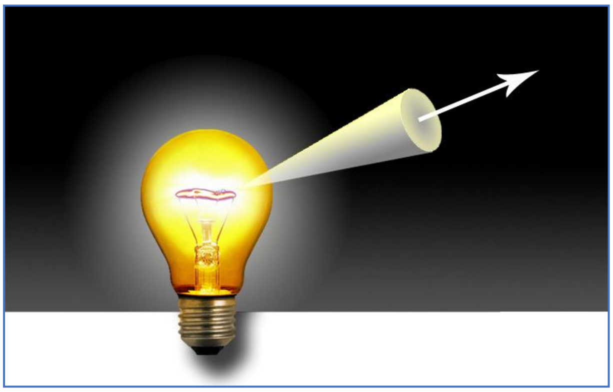

Figure 2: Luminous intensity is the luminous flux emitted in a specified direction per unit of solid angle, units of lumens per steradian, simplified to the candela.

Luminous intensity (reported in candelas) is related to illuminance (in lux) by a fundamental rule of physics called the inverse squared law. For a theoretical "point source" of light, the beam propagates with equal intensity at all distances, but with the illuminance decreasing with the square of the distance between lamp and receiver. Thus, by knowing the value of the luminous intensity in a specified direction, one may directly compute the illuminance in lux delivered onto a surface at a known distance.

How Are Photometric Data Files Produced?

Figure 3: A 3m diameter lamp measurement integrating sphere (courtesy of Labsphere).

Almost every photometric test laboratory is equipped with two main items of optical test equipment. The **integrating sphere** (Figure 3) is used to measure total luminous flux (lumens) as well as colorimetric parameters of the light source (correlated colour temperature – CCT, chromaticity and colour rendering). The integrating sphere is relatively quick and easy to set up and use, so is often relied upon for both the incoming QA of lamps and LEDs, and the production testing of finished products.

The one important thing that an integrating sphere measurement can't tell you is how much light from the luminaire emits in a particular direction, this being the directional luminous intensity. For this measurement you need a piece of equipment called a **goniophotometer** (Figure 4). Depending on what type of optical detector is used, this may also be called a **goniospectroradiometer**. The function of this equipment (let's refer to it as a "goniometer" for simplicity), is that it generally rotates and tilts the device under test about a fixed photodetector. Other mechanical implementations exist, such as goniometers that rotate the fitting about one axis, and rotate the detector about the other, or goniometers that again rotate the fitting about one (usually vertical) axis, and rotate a large mirror about the other, together with a fixed detector.

Regardless of the mechanical configuration, all goniometers share the same fundamental attribute, which is to automate (as much as possible) the measurement of directional luminous intensity from the sample and to format the test results into a computer readable format, such as the aforementioned .IES or .LDT files.

It should be noted that whereas an integrating sphere can't take the place of a goniometer, the reverse isn't true. The summation of the directional luminous intensity values over 2π or 4π steradians from a goniometer yields the total luminous flux from the light source. Thus, a goniometer test will tell you the number of lumens emitted by the source, albeit in a measurement that can take rather longer to perform than in an integrating sphere.

Figure 4: The compact LAMP 30 2-axis motorised goniophotometer from SSL Resource

Photometers Versus Spectroradiometers

One further variation on the theme of goniometers is the choice of photodetector used to record the directional luminous intensity. A goniophotometer is a goniometer system that employs a filtered photometer, whereas a goniospectroradiometer uses a spectrometer. A spectrometer that is calibrated radiometrically is referred to as a spectroradiometer.

Photometers & Colorimeters

A photometer sensor is normally comprised of a silicon photodiode over which is placed a special green coloured filter. The combined spectral response of the filtered photodiode is designed to closely match (as far as possible) the photopic sensitivity of the human eye (see Figure 5). The photopic response of the human vision system strongly favours green coloured light, with blue and red light being perceived as less intense. Thus the photopic sensor ranks the brightness of light sources in close agreement to how the human vision system would perceive them.

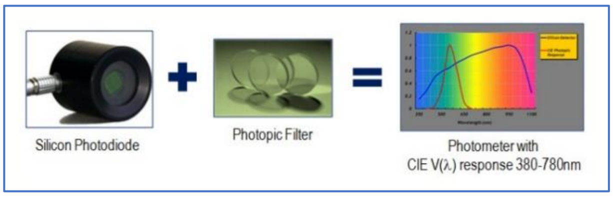

Figure 5: the anatomy of a photopic response photodetector ("photometer")

Some goniophotometers employ a colorimeter instead of a photometer. Conceptually similar to a photometer, a colorimeter employs three photodiodes, each one filtered to one of the CIE tristimulus colour matching functions. As with a photometer, a colorimeter will record the illuminance from the light source mounted on the goniometer frame, but in addition it will report the colour of the sample in terms of CIE chromaticity coordinates and correlated colour temperature (CCT) in units of Kevin.

One point of clarification is necessary at this point. A luminous intensity meter does not exist as such. Instead, one measures illuminance (in lux) directly, and then computes the intensity (in candelas) using the aforementioned inverse squared law. Thus the photodetector is actually a photometer (or colorimeter) configured for measuring illuminance, otherwise known in the vernacular as a "lux meter".

Spectrometers & Spectroradiometers

A spectrometer is an optical detector that separates the incident light into its component wavelengths, which are imaged onto a linear or 2D photodiode array (see Figure 6). Each detector in the array is called a "pixel" and receives one narrow band of wavelengths (or small section of the colour spectrum). The spectrometer thus records a spectrum (more correctly, a spectral power distribution) of the light source under test. With appropriate calibration and input optics, a spectrometer becomes a spectroradiometer. The photopic response of the human vision system is applied mathematically to the measured spectrum, thus the photometric values (illuminance, luminous intensity) as well as colour parameters are derived by computation from the raw spectral data.

Whereas compact, array spectrometers are a fairly recent innovation, photometers and colorimeters have been used for many decades, and in some quarters, tend to be unfairly dismissed as being somewhat old fashioned. This is a dangerous assumption, as the reality is that the filtered photometer (or colorimeter) is relied upon as the primary sensor in nearly all professional, accredited lighting test laboratories and in National Measurement Institutes (NMIs). The reasons for the use of photometers over spectrometers are manifold, and include a vastly superior dynamic range, many times higher sensitivity and lower noise, a lower calibration uncertainty and higher longer term stability.

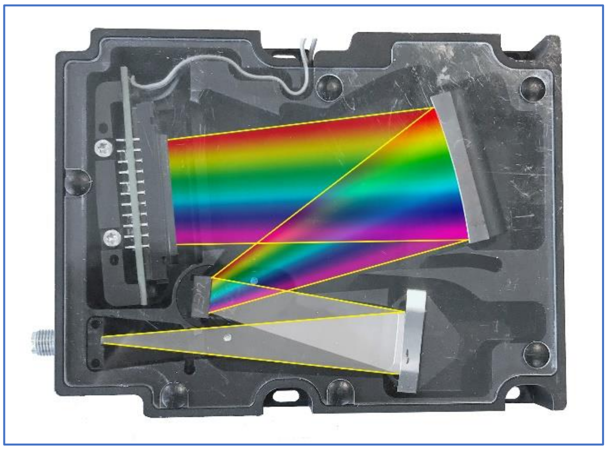

Figure 6: X-ray schematic of a compact array spectrometer showing the angular separation of the component wavelengths from the incident beam of white light (courtesy of Avantes).

Goniospectroradiometers – Caveat Emptor!

Some manufacturers of goniometer systems based upon spectrometers promote their product's versatility, claiming that they are the perfect "one stop shop" for all of your photometric measurement needs. This is disingenuous and requires careful consideration. While it is indeed the case that a goniospectroradiometer is very versatile (allowing the measurement of all photometric, colorimetric and colour rendering parameters), there are drawbacks compared to a traditional goniophotometer.

Watch the Cost

The first – and most obvious concern – is that a spectroradiometer is a more expensive device than even a good quality filter photometer. Comparing like-with-like, a goniospectroradiometer will cost about 20% more than an equivalent gonio-photometer. Given that .IES and .LDT photometric files do not require that CCT or CRI are measured, there is no explicit requirement for the added cost and complexity of a spectroradiometer in budget-conscious goniometric applications.

Dynamic Range & Sensitivity

The main technical arguments against array spectrometers used in goniometry concerns their more limited dynamic range and relative lack of photometric sensitivity. Consider that the silicon photodiode used in a filter photometer has an inherent dynamic range (the range of brightness levels that it can detect, from the noise floor right up to saturation) that extends from 1pW to 1mW (10^{-12} to 10^{-3} Watts). This is a 9-decade dynamic range, whereas array spectrometers of the type used in goniospectroradiometers provide a much more limited dynamic range. One common system uses a spectrometer with a specified dynamic range of just 3000:1, so just 4 decades, with a signal-to-noise ratio of 300:1.

The absolute sensitivity of a spectrometer also compares poorly against a filter photometer. Based on a measurement distance of 1m, a good quality filter photometer will be capable of measuring luminous intensity values as low as 0.001 candelas, whereas a spectrometer will struggle to detect much below 0.5 candelas.

Note that the greater the distance between light source and spectrometer, the lower the light level received will be (in terms of illuminance in lux). This is as a result of the aforementioned inverse squared law. For the case of low power yet highly directional light sources (such as spotlights), you may even find that a spectrometer lacks sufficient sensitivity to even detect the beam.

These limitations can result in excessive signal-to-noise problems with the measured spectrum (shown in Figure 7) which leads directly to significant errors in the computed photometric and colorimetric parameters reported by the spectrometer.

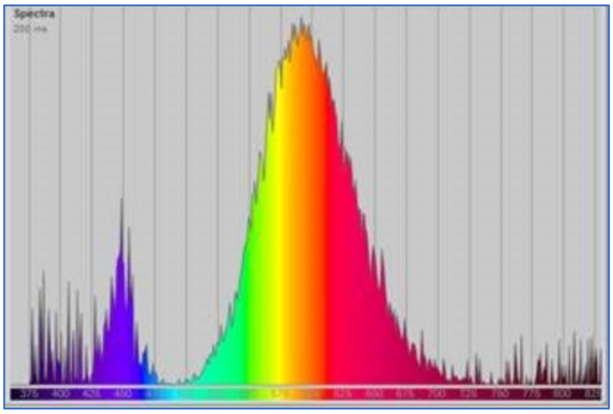

Figure 7: The limited dynamic range and lack of sensitivity of an array spectrometer can lead to very noisy spectra and significant errors in the computed photometric and colorimetric parameters

The Need for Far-Field Measurements

To make matters even more complicated, it is vital that the sensor (photometer, colorimeter or spectrometer) in any goniometer system is positioned far enough away so as to be in the photometric "far-field" for the luminaire under test. This is to ensure that the beam from the test light source is fully formed. If you measure a light source in the near-field, then the illuminance and luminous intensity will be measured erroneously low (by some tens of percent) and the shape of the beam will also be misreported. The narrower the beam angle, the greater the distance to the photometric far-field. The concept of near-field versus far-field is illustrated below (see Figure 8).

In accordance with the guidelines stated in the measurement standard CIE S025, the far-field distance for a simple, diffused, wide angle beam will be at a minimum of 5x the "luminous aperture" of the fitting. The luminous aperture is either the diameter of a downlighter or the diagonal of a rectangular luminaire. So for a standard 600 x 600mm ceiling luminaire, the minimum measurement distance will be at about 4.5m from the light source. For a 1200 x 600mm fitting, the safe working distance is about 7m.

EN 13032 part 4 goes beyond even these requirements and advises the following. That for a wide angle (Lambertian type) beam, the far-field distance should be at ≥10x the luminous aperture. For narrow angle sources (<30° beam angles), both CIE S025 and EN13032 part 4 recommend that the measurement distance should increase to ≥15x the luminous aperture. Furthermore, for luminaires comprised of widely spaced, discrete emitters, the working distance should be computed as being ≥15x the sum of the luminous aperture and the separation between emitters.

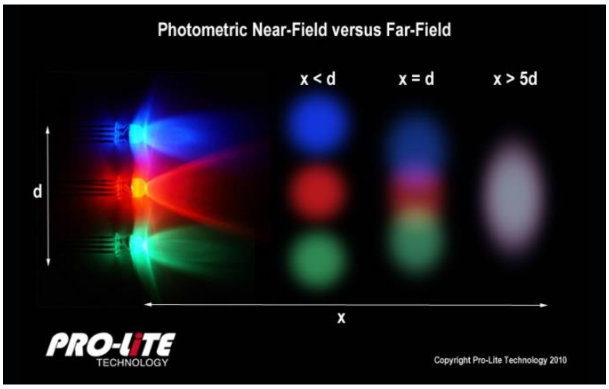

Figure 8: This graphic illustrates the propagation of a beam from a light source, from the near-field through to the far-field, in which the beam is "fully formed". Goniophotometric measurements must always be performed in the far-field.

Narrow beam angle light distributions present a considerable challenge for goniophotometric measurement. Simply stated, the narrower the beam (or the more collimated), the greater the photometric distance you should be measuring at. In the case of one 15° downlighter tested at Pro-Lite, our experiments showed that the photometric far-field distance was more than 40x the luminous aperture of the spotlight. For vehicle headlamps, UNECE regulations stipulate the photometric measurements must be performed at a distance of 25m from the source.

If you are in any doubt as to whether you are making your goniometric measurements in the far-field, a simple measurement of the illuminance versus distance will reveal whether your results follow the inverse squared relationship.

The restricted dynamic range and reduced sensitivity of goniospectroradiometers means that you are likely to have to reposition the spectrometer at a distance that obeys the far-field criteria for the sample under test, but not so far away as to reduce the illuminance to a level where signal-to-noise errors start to dominate. For high power light sources, you need to be aware of the possibility of saturating the spectrometer. In that case, the solution is to exploit the inverse squared rule and move the detector far enough away so as to avoid this issue.

In practical terms, you may need to move your spectrometer to an appropriate working distance every time you test a different type of luminaire. While this sounds simple in theory, the critical need to precisely realign the spectrometer to the goniometer each time you move the detector will be time consuming and inconvenient.

Some manufacturers of goniospectroradiometers offer a Z-axis translation rail for positioning the spectrometer at different distances from the goniometer frame, but this is only making a virtue out of a necessity. Moreover, over the range of travel on the rail, the difference in signal level will only add a decade or so to the already limited dynamic range of the spectrometer. This approach does not therefore compensate for the inherent lack of sensitivity and dynamic range of the spectrometer compared to a filtered photometer.

In comparison, the wider dynamic range and greater sensitivity of a filtered photometer (or colorimeter) means that you can leave it at a fixed position regardless of the type of product being tested. In placing the photometer safely in the far-field, its 9-decade dynamic range will ensure that even low intensity portions within the light distribution will be detected with good signal-to-noise. Equally, low powered sources with narrow beam angles can be measured without needing to reposition the photometer.

One rather more subtle concern with the use of spectrometers in goniometric applications arises due their complex optical design. Standards such as IES LM-79 and EN 13032-4 require that you quote an uncertainty budget for your measurements. Moreover, should a photometric laboratory ever wish to attain ISO 17025 accreditation, an error analysis must be provided. The calculation of an uncertainty budget for a goniospectroradiometer is notoriously complex, whereas that for a photometer system is relatively straightforward.

If the measurement of colour temperature as a function of angle is required, for example, to evaluate the colour "zoning" sometimes present with remote phosphor LED sources, one may substitute a filter colorimeter for the photometer. This maintains all of the advantages of the filter photometer, with none of the drawbacks of the array spectrometer.

Stop-and-Go Versus On-the-Fly Goniometer Motion

The inverse squared rule tells us that moving your detector closer to the light source increases the illuminance that it sees, the better to cope with low intensity beams. Conversely, moving your detector further away, reduces the illuminance, which is how you handle the most intense beams. However, the need to satisfy the far-field criteria imposes a minimum distance between light source and detector, thus limiting how much light the photometer or spectrometer will receive. As stated previously, the vastly increased dynamic range and sensitivity of a filter photometer renders goniophotometers immune to problems of signal-to-noise and avoids the need to move the detector when testing different types of light sources.

What of goniospectroradiometers? Moving the spectrometer allows it to handle different levels of light, but what if the light source has zones of both very high and very low intensities that have to be measured during the same goniometric scan? That can become an insurmountable problem. Consider the case of light sources that are both relatively dim and have a narrow beam angle or complex beam structure. Examples include headlamps (tested at the regulation 25m), streetlamps and spotlights.

The measurement distance chosen will be far away from the light source so as to obey the far-field criteria, while the spectrometer exposure times will be set for the direction of peak intensity at that distance. If the goniometer motion is of the "stop-and-go" variety (where the goniometer motors to a new angle, stops and the measurement is made), the spectrometer exposure can be adjusted for the intensity in that part of the beam.

Unfortunately, that is not how most goniospectroradiometers operate. In the interests of speed, these devices generally operate "on-the-fly". This means that the goniometer doesn't stop at each new angle, instead the motion is continuous. Therefore, there is no opportunity to adjust the spectrometer's exposure time for differing levels of intensity. The spectrometer's exposure time is simply set for the direction of peak intensity, resulting in measurements in low intensity regions in the beam suffering with a high level of noise.

This problem is illustrated in the polar intensity diagram shown below (Figure 9), recorded using a goniospectroradiometer. Here, the reverse fraction of the light emitted from the luminaire is so dim relative to the forward flux as to lead to clearly visible noise in that part of the intensity plot.

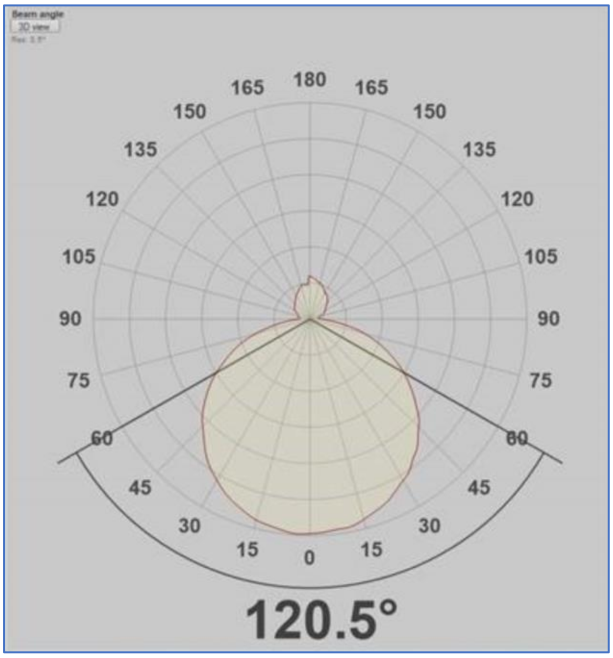

Figure 9: A polar intensity diagram for a luminaire with a weak upwards/rearwards emission - note the noise on that section of the intensity plot

The Problem is Glaringly Obvious

One may argue that increased errors in regions of low intensity are not the end of the world. However, some of the derived photometric and colorimetric parameters that are important to lighting designers are heavily weighted by the performance of the luminaire in regions of low intensity at high angles.

Take for example the UGR, which is the Unified Glare Rating of a luminaire. To avoid visual discomfort (or worse), UGR is a key metric that can be reported from the goniometer or derived from a photometric data file. Noise (i.e. lack of signal) in the measured luminous intensity at high angles of incidence in the beam will lead to very large errors in the computed glare rating for that luminaire.

Similarly, the measurement of SDCM (Standard Deviation Colour Matching) angular colour uniformity within a beam is a vital metric that can be heavily distorted if the measured colour is falsely reported due to noise in the beam at high angles.

Why would you wish to measure zonal SDCM? Colour "zoning" is a commonly encountered phenomenon with white LED luminaires. The fluorescent conversion of native blue LED light through a yellow phosphor to create white light is a function of the thickness of the phosphor (or the optical path length) that the blue light encounters. This results in a distinct colour shift within the beam (see Figure 10). In the centre of the LED beam where the effective phosphor thickness in at a minimum, less of the blue light is converted to longer wavelengths. At higher angles, more of the blue light is converted, so there will be a greater proportion of longer wavelength green and red light in the beam.

Figure 10: Phosphor white LED colour zoning – note the high CCT (blue tint) in the centre of the beam, surrounded by a yellow-tinted anulus.

The effect of all of this is to create a beam that is clearly blue-tinted in its centre, transitioning to a more yellow-tinted anulus surrounding the blue centre. Figure 11 shows the a polar chart for the variation of CCT (correlated colour temperature) for a phosphor white LED. It can be clearly seen that the CCT in the centre of the beam is about

7500K, dropping to about 4500K at 60° inclination. The higher levels of measurement noise encountered at higher angles with spectroradiometers means that the true colour difference (the SDCM) within the beam can be misreported.

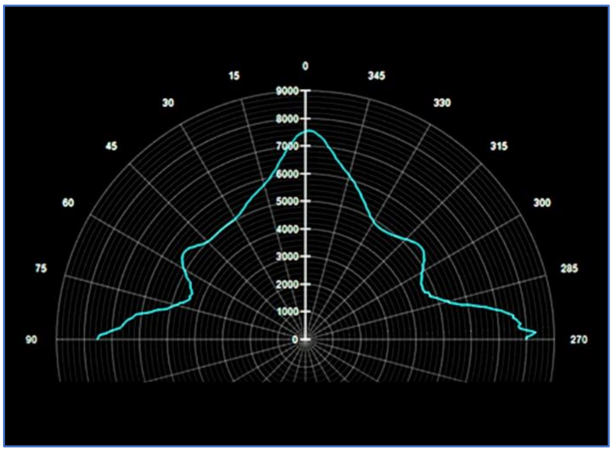

Figure 11: Plot of CCT versus angle for a phosphor white LED shows variation of >3000K from centre to edge of beam

All of which is not to suggest that spectrometers should not be used for goniometric measurements. Rather, a spectrometer can be used as a supplementary detector, with a photometer or colorimeter serving as the primary measurement device. With the photometer placed in the photometric far-field and providing accurate readings of absolute luminous intensity, the spectroradiometer can be positioned (and easily repositioned) at a convenient location and relied upon for relative spectral measurements.

In Conclusion

While a goniospectroradiometer may appear superficially attractive as an "all-in-one" solution for photometric testing, the reality is that goniophotometers are chosen by professional lighting test laboratories for very good reasons. Quite apart from their lower costs, photometers provide a much wider dynamic range and greater photometric sensitivity, both of which promote the highest possible measurement accuracy regardless of the power or beam shape from the light source under test.

The sensitivity and wider dynamic range of photometers over spectrometers eliminates the need to constantly reposition and realign a spectrometer each time you set up to measure a different type of product. When following the CIE S025 far-field guidelines for the minimum separation between light source and detector, one may position a photometer at a fixed position suitable for measurements of any product, whereas a spectrometer will need to be moved (and the goniophotometer realigned) to cope with differing lamp powers and beam shapes.

The ability of a goniospectroradiometer to measure not just photometric but also colorimetric and colour rendering parameters is desirable in some applications, but in that case, we recommend that the photometer is used as the primary meter, with a spectroradiometer employed as a secondary meter. The spectroradiometer can be located separately from the photometer, and close enough to the goniometer so as to not suffer signal-to-noise errors.

A portable spectroradiometer (see Figure 12) can be deployed as a standalone meter for the recording of axial colour and colour rendering parameters to satisfy that requirement. The added benefit of this approach is that the spectroradiometer can be taken out of the photometric laboratory and used for site surveys and for on-site verification of lighting schemes, post installation.

Figure 12: The Spectraval is a portable, hybrid spectroradiometer that measures spectral irradiance, spectral radiance, luminance, illuminance, CCT, CIE chromaticity and colour rendering. It can be used in the photometric laboratory, as well as taken out for site surveys and lighting scheme verification (courtesy of JETI).

About the Author

Robert Yeo is an optical and laser physicist with over 30 years' experience in light metrology and photometry. Having started his career at Labsphere – the integrating sphere company, Robert was a co-founder of Pro-Lite in 2002 and formed Photometric & Optical Testing Services (POTS) in 2011 as an independent lighting test laboratory. In 2005, Robert developed a training course in photometry and practical light measurement that has since been delivered to over 500 scientists and engineers worldwide. Robert is proud to have helped train the photometry specialists who today operate several of the UK's leading independent lighting test laboratories.

About Pro-Lite Technology

Pro-Lite is the European channel partner for a range of photometric and goniophotometric test equipment from companies such as Labsphere (integrating sphere photometers), SSL Resource (goniophotometers & goniospectroradiometers), Konica Minolta (photometers & colorimeters), JETI (spectroradiometers) and Westboro Photonics (imaging photometers and colorimeters).

Pro-Lite Technology Ltd is part of the Pro-Lite Group of Companies, which includes Photometric & Optical Testing Services, SphereOptics Germany, Pro-Lite France and Pro-Lite Iberia.

For More Information

For more information on Pro-Lite's range of lighting test equipment, rental services and photometry training workshops, please go to the Pro-Lite web site.