



The Science of Goniophotometry



A Technical Note by
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Introduction

This technical note reviews the science of goniophotometry – the measurement of luminous intensity as a function of angle from a light source. The topics addressed here are photometry – measuring light sources as the human observer would perceive them, the different types of goniometer motion (as defined by the Illuminating Engineering Society of North America, IESNA), the concept of photometric distance and the importance of making goniometric measurements in the photometric far-field.

What is Goniophotometry?

Photometry is the science of measuring the brightness of light sources as the human vision system would rank them. The human eye has a characteristic spectral sensitivity under daylight levels of illumination such that for the same absolute (radiometric) amount of light, we perceive green coloured light as much brighter than the same amount of light in the blue or red part of the spectrum. The relationship between wavelength in the 380-780nm visible light band and the perceived brightness of the light at each wavelength is defined by the CIE spectral luminous efficiency function for photopic vision, which for daylight levels of illumination is known as the "photopic" response.

Goniophotometry is the measurement of the amount of light shining in a specified direction. The word "gonio" derives from the Greek, meaning

angle. In other words, goniophotometry is the act of measuring the angular (or spatial) distribution of light from a light source. A laser can be a very powerful source of light, but the beam is generally of a small diameter and travels with near perfect collimation. You therefore would not wish to use a laser to illuminate a living or work space. Conversely, an incandescent lamp is a near-perfectly isotropic radiator, producing almost equal intensity in all directions. This is one reason why tungsten lamps rather than lasers prove to be a better source of illumination for lighting our homes and work places.

One of the key reasons why goniophotometry is so important is for the purpose of creating so-called "photometric data files". A photometric file for a lamp or luminaire is a machine-readable data file containing a table of the luminous intensity values for the light source as a function of angle, recorded over a 2π steradian hemisphere or a complete 4π steradian sphere. Photometric files are normally compiled into either of two industry-standard formats, IES (.ies) or EULUMDAT (.ldt). The photometric data for a light source can then be imported into lighting design software to simulate the level of illumination and beam pattern on a surface, helping to create lighting schemes without recourse to time consuming and expensive physical models.



What is a Goniophotometer?

A goniophotometer is a measurement device that combines two key elements, a photometer and a goniometric motion stage. The photometer is the photoelectric light meter that mimics the photopic spectral sensitivity of the human eye, turning incident illumination into an electric current. Some photometers double up as colorimeters, allowing for the measurement of both the amount and the colour (chromaticity, correlated colour temperature) of the light source.

Sometimes, a spectroradiometer is used either instead of – or as a supplementary photodetector to – the photometer or colorimeter. A spectroradiometer measures the amount of light present at each wavelength and then computes the photometric and colorimetric parameters with reference to the CIE photopic or colorimetric observer functions, held in software as look-up tables. Due to their relatively limited dynamic range and lack of sensitivity, we generally only recommend the use of spectroradiometers as supplementary detectors and not instead of the usual photometer or colorimeter. Instances where you would wish to use a spectroradiometer are when you need to know the colour rendering of the light source, or when you need to know the radiometric performance of the lamp, for example with UVC germicidal disinfection lamps or with horticultural (plant growth) lamps. For further discussion on this topic, please refer to the Pro-Lite Technical Note "Goniophotometry versus Goniospectroradiometry".

We should at this point define what we mean by "the amount of light". For any kind of lamp or luminaire, the photometric property of interest in goniophotometry is the luminous intensity. Luminous intensity is the proportion of the total luminous flux emitted by the lamp, shining in a specified direction, per unit of solid angle (see Figure 1). The units used are lumens for luminous flux and steradians for solid angle, but for

convenience, we refer to the lumen per steradian as the more familiar unit called the candela (cd).

Luminous intensity (in candelas) is distinct from other photometric parameters such as the total luminous flux (units of lumens), the illuminance (units of lumens per square meter, or lux) and the luminance (units of lumens per steradian per square meter, or candelas per square meter). In photometry, luminance (cd/m²) is what you measure from a display or sign, whereas luminous intensity (cd) is that property of interest from a lamp or luminaire.



Figure 1: 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.

Turning next to the goniometer part of the equation, this is the device that (usually) rotates and tilts the light source under test about a fixed photometer position. Students of photometry may be taught to measure a lamp mounted on a simple, mechanical engineering turntable but in commercial test laboratories, we generally find much more sophisticated motorised goniometer stages that operate under computer control.



Goniophotometer Design

For a complete description of the output of a lamp or luminaire, we must measure the luminous intensity over the range of angles that the light source radiates into. For a downlighter-type luminaire, this means that we must measure the light output over a hemisphere (2π steradians of solid angle), whereas with other types of light source (for example, incandescent lamps), we must measure over a complete sphere (4π steradians). The design of different types of goniophotometers can support either 2π or 4π motion.

How this motion is implemented varies greatly from manufacturer to manufacturer. In the case of most commercial goniophotometers, the light meter (photometer, colorimeter and/or spectroradiometer) is placed at a fixed position and receives light from the device under test as it is rotated and tilted by the goniometer. Alternative designs do exist and these include goniometer stages that rotate the lamp about its azimuthal axis while the photodetector rotates in an arc about the lamp, referred to as "moving detector" goniophotometers. A variation on that theme is the "moving mirror" type of goniophotometer, whereby the lamp is again rotated about its azimuthal axis, and a mirror rotates in an arc about the lamp, reflecting the light to a fixed photodetector placed at a distance away from the goniometer. Yet another goniophotometer design rotates the lamp about its azimuthal axis, and the light is received onto an array of photodetectors arranged about an arc about the lamp.

The differences in the mechanical design of most goniophotometers are subtle – and often trivial – but for certain types of lamps, how the product moves during a goniometer scan is vitally important. What can be critical for some lamp technologies is whether the light source changes its orientation with respect to gravity (its burning position) during a scan. Incandescent and fluorescent lamps generally emit the same amount

of light regardless of their orientation with respect to gravity. Conversely, some types of discharge lamps (notably metal halide), suffer from a significant change in light output depending upon whether they are held in a parallel or perpendicular direction with respect to gravity. For these types of lamp, you must firstly mount them such that they are operated in the intended (design) orientation, and secondly ensure that the burning direction doesn't change with respect to gravity during a goniometric measurement.

LED-based solid state lighting (SSL) is also generally immune to the orientation in which it is operated. However, this assumes that the product enjoys adequate heat sinking. In some cases, a small difference in light output can be observed depending upon the orientation of the light source with respect to gravity, although nothing like as much as with metal halide discharge lamps.

IES Goniometer Motion Types

The Illuminating Engineering Society of North America (IESNA, often abbreviated to just "IES") published a standard in 2001 called LM-75-01 (since updated in 2019 to LM-75-19) which defines three generic types of goniometer motion. These are referred to as type A, B and C and these are illustrated schematically below (Figures 2-4).

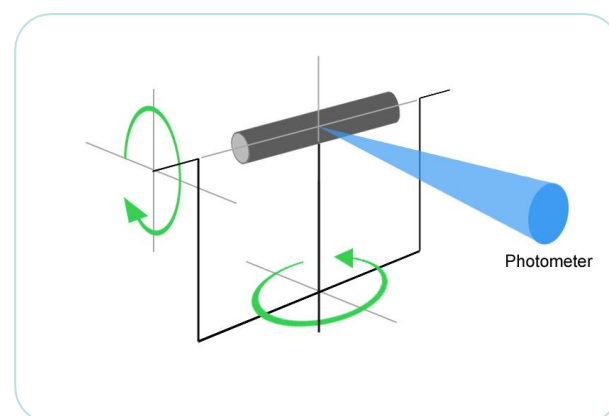


Figure 2: IES type A goniometer motion.

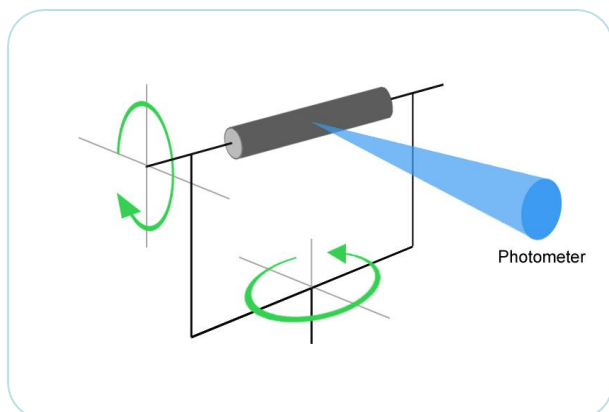


Figure 3: IES type B goniometer motion.

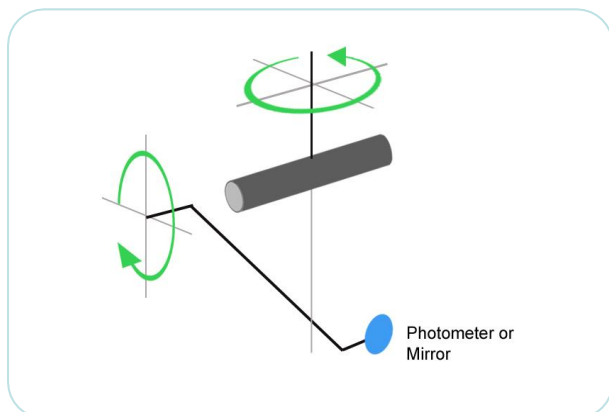


Figure 4: IES type C goniometer motion.

The motion of type A and B goniophotometers is very similar, and for both cases the device under test is rotated $\pm 90^\circ$ about orthogonal horizontal and vertical axes. We refer to the corresponding type A or B coordinate system as horizontal-vertical (H-V or X-Y).

A goniophotometer that employs type C motion rotates the device under test about an azimuthal axis (the nadir angle which is usually aligned along the polar axis of the coordinate system), while the other axis of motion is termed the elevation (or inclination) axis. The type C spherical coordinate system is referred to as θ - ψ , with θ (theta) being the elevation axis and ψ (psi) being the azimuthal axis.

In a type A or B goniophotometer, the orientation (burning position) of device under test tilts with respect to gravity during a scan. With a type C

goniophotometer, the device under test maintains a constant orientation with respect to gravity during the measurement. To avoid errors arising from a lamp or luminaire tilting with respect to gravity, international lighting standards such as IES LM-79-18, EN 13032-4 and CIE S025 require that the sample is measured using a type C goniophotometer. In addition, a correction factor should be determined and applied to the goniometer readings if the sample is mounted on the goniophotometer in an orientation that is different to its design orientation.

In general, type A/B motion goniophotometers (see Figure 5) are used when measuring directional lighting products. Typical applications include the testing of vehicle lighting (e.g. automotive headlamp and marker/side lamps) as well as other types of transportation and avionics lighting and signalling devices (e.g. VMS traffic signs).

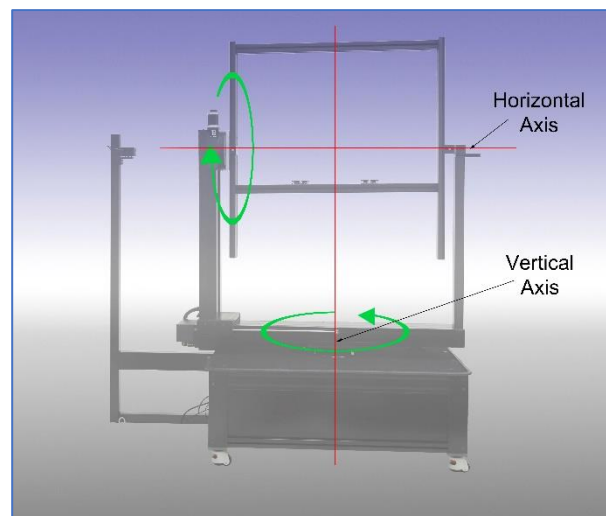


Figure 5: Type B horizontal/vertical motion – the device under test rotates about a horizontal and a vertical axis (the goniophotometer shown is the SSL Resource AUTO-100).

Type C goniophotometers are usually chosen when measuring lamps, luminaires and architectural lighting products. Some manufacturers (for example, SSL Resource, Finland) have designed type C goniophotometers that can be converted by the user to type B motion (and vice versa) with the purchase of an accessory kit. This flexibility allows one goniophotometer to accommodate almost any



kind of light source, both directional vehicle lighting as well as architectural luminaires.

The moving detector or moving mirror goniophotometers employs type C motion in which the device under test is held in a vertical orientation, either shining down ("base-up) or shining up ("base down"). The lamp's orientation with respect to gravity does not vary during a measurement. The first axis of rotation is about the vertical azimuthal axis, ψ (psi), over a range of 0-360°. The second axis of rotation is the elevation or inclination, θ (theta), and is applied to either the mirror or the detector which then rotates about the light source, over a range of 0-180°. A moving detector type C goniophotometer is shown below (Figure 6).

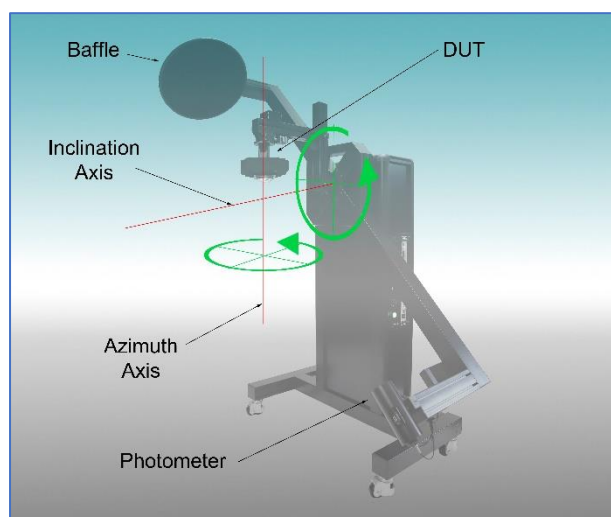


Figure 6: Type C moving detector motion – the device under test (DUT) is held in either a vertical base-up or base-down orientation and rotates about its vertical azimuthal axis while the inclination (elevation) motion is performed by the photometer moving in an arc about the lamp (the goniophotometer shown is the SSL Resource DECO 27).

Moving mirror or moving detector type goniophotometers can sometimes be relatively bulky, so a popular variation on the theme is the type C horizontal motion design (see Figure 7). In a type C horizontal goniophotometer, the device under test is held in a horizontal orientation and rotates about a horizontal azimuthal axis, while the sample's second axis of motion (elevation or inclination) is about an orthogonal vertical axis.

As with the type C vertical configuration, the device under test does not tilt with respect to gravity during a measurement. However, if the sample is not held in its intended or design orientation (for example, a ceiling fixture that would normally shine vertically down but is mounted in a vertical plane and shines horizontally), a correction factor must be determined and applied to the goniophotometer readings. The goniophotometer manufacturer SSL Resource (Finland) offers an accessory device for their equipment called the Burn Position Corrector (BPC) that automatically determines a correction factor and applies it to the directional luminous intensity readings.

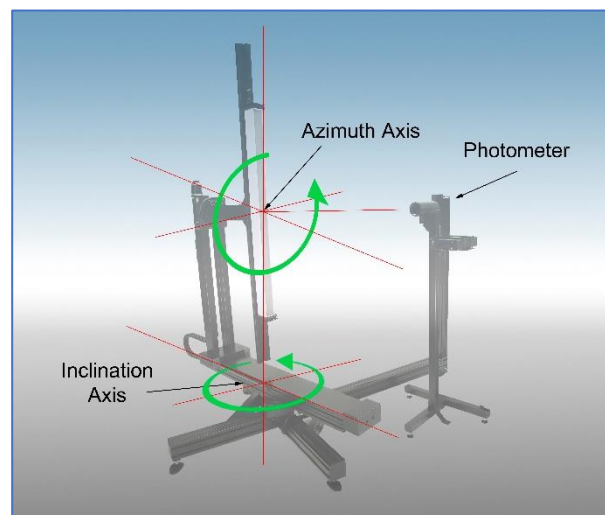


Figure 7: Type C horizontal motion - the azimuthal axis lies in a horizontal plane (the goniophotometer shown is the SSL Resource C-1 LAMP 200).



Photometric Distance

A very important factor to understand when performing goniophotometric measurements of lamps and luminaires is the limiting photometric distance for the device under test. Also referred to as the far-field distance, this is the minimum separation between emitter and receiver at which the lamp behaves as a point source. In the far-field, the beam from the lamp propagates with constant luminous intensity in that direction. At the same time, in the far-field, the illuminance follows an inverse squared relationship. The inverse squared rule states that for a lamp in the far-field, the luminous intensity is a constant at all distances, whereas the illuminance decreases with the square of the increase in separation between source and receiver. This is shown below (see Figure 8) with a lamp that delivers an illuminance of 400 lux at a certain separation (x), while at double that distance ($2x$), the illuminance drops to $400/2^2 = 100$ lux.

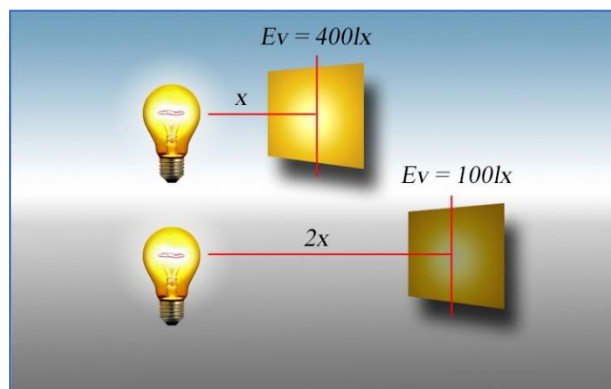


Figure 8: The inverse squared relationship whereby the illuminance from a point light source in the far-field decreases with the square of the increase in separation between source and receiver.

The importance of making far-field measurements in goniophotometry can be understood as follows. The output of a lamp or luminaire is measured using an illuminance photometer in units of lux. Provided that the measurement has been properly performed in the far-field, luminous intensity values can then be accurately calculated using the inverse squared rule, as the product of illuminance and the square of the separation between lamp

and photometer. The IES or LDT photometric file is then compiled using these computed intensity values. This is convenient because as previously stated, luminous intensity is invariant in the far-field. When the photometric data file is then utilised in lighting design software, the illuminance from the lamp at any distance (in the far-field) can then be computed by the software by application of the inverse squared rule in reverse, illuminance being the luminous intensity divided by the square of the distance.

This prediction of illuminance would fail should the original goniophotometric measurement have not been performed in the far-field in the first place. In the near-field, the photometer is sampling just part of the beam and thus any intensity value computed from near-field illuminance will be significantly lower than the true far-field intensity.

It is therefore vitally important to perform goniophotometric measurements on lamps and luminaires in the far-field, but where exactly is this for any given light source? The concept of near-field versus far-field in photometry is shown below (Figure 9). The "luminaire" in this illustration is comprised of a linear array of three RGB coloured LEDs, the light from which additively mixes to create white light in the far-field. We define a parameter called the luminous aperture (d in Figure 9), which is the maximum dimension of the lit area of the luminaire under test. This could be the diameter of a circular downlighter fitting, the length of a linear or tubular lamp, or the diagonal of a square or rectangular luminaire. Considering next the separation between the plane of the light source and the surface being illuminated (x), we regard distances of up to $x = d$ as being fully near-field. It is only when $x > 10d$ that the beam of light has (probably) entered the far-field. For further information on this topic, please refer to the CIE publication 70-1987 "The Measurement of Absolute Luminous Intensity Distributions".

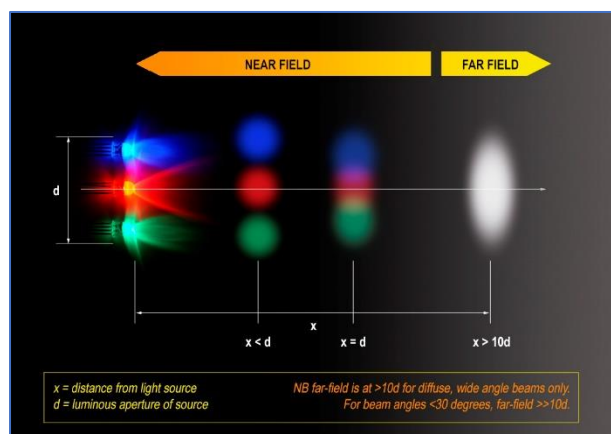


Figure 9: The concept of near-field versus far-field - in the photometric far-field, the emitter behaves as a point source, the luminous intensity becomes constant and the illuminance follows the inverse squared rule. The beam pattern from the light source is illustrated at increasing distance (left to right) from the light source.

The 10d far-field multiple can be safely applied to any diffused, wide angle lamp or luminaire. However, care must be taken with lamps with narrow beams, or luminaires that are comprised of an array of widely spaced emitters. The far-field distance for these types of light source will be much greater. EN 13032-4 and CIE S025 both recommend using a 15d multiplier for sources with beam angles of $<30^\circ$. Meanwhile for luminaires comprised of widely spaced, discrete emitters, the working distance should be computed as being ≥ 15 times the sum of the luminous aperture and the separation between emitters.

In the automotive field, vehicle lighting regulations (e.g. UNECE R20, R98, R112, R122) stipulate that headlamps must be measured at a distance of 25m. Research has shown that measurements of headlamps performed at ~ 10 m for comparison testing correlate closely with the 25m far-field results, but for type-approval testing, the measurements must be performed at the regulation 25m.

In summary, we can state that the narrower the divergence (beam angle) from a lamp or luminaire, the greater the distance to the far-field. The beam from a laser probably never reaches the far-field, because it is nearly perfectly collimated. However

one example that illustrates the problem with narrow angle sources that the author encountered was an LED spotlight with a beam angle of 15° . The luminous aperture for this lamp was 25mm. Using the traditional 10 times rule of thumb, you might expect the photometric (far-field) distance to be at 250mm. This was not the case, with experiments revealing that the limiting distance was at ~ 750 mm, beyond which the illuminance followed the inverse square rule and the luminous intensity was constant. This is a 30 times multiplier, which illustrates the need to verify that you are truly in the far-field when measuring very narrow angle light sources.

Sphere or Goniophotometer?

Before we finish this review of goniophotometry, it is worth explaining when to use a goniophotometer and when to use an integrating sphere. An integrating sphere is used to measure the total luminous flux (in lumens) from a lamp or luminaire placed inside it (see Figure 10). A goniophotometer is used to measure directional luminous intensity and for creating photometric data files. However, the summation of directional luminous intensity over 2π or 4π steradians yields total luminous flux, meaning that you don't need an integrating sphere to measure the lumens from a light source. Indeed, we find certain equipment manufacturers claiming that their goniophotometer dispenses with the need for an integrating sphere.

That argument is slightly disingenuous as there is a place for both instruments in most photometric laboratories. Compared to a goniophotometer, an integrating sphere is both faster and simpler to operate. It is also arguably a more accurate measurement, at least with regard to the possible sources of error that can arise with a goniophotometer. These include not making measurements in the far-field for the particular light source, not making intensity measurements with a high enough resolution in those regions of the beam with high gradients and sampling a



quadrant of the beam and then incorrectly assuming rotational symmetry when extrapolating to the full beam.



Figure 10: A 3m diameter integrating sphere for measuring total luminous flux and colour of large luminaires (image courtesy of Labsphere Inc).

In general, an integrating sphere is the ideal tool for routine quality assurance testing, both of incoming LEDs and of the performance of the finished product. The ideal situation would be for the photometric laboratory to use both a goniophotometer and an integrating sphere.

Summary

This paper has explained the different types of goniophotometer motion (IES type A, B & C) and explained the importance of not tilting the burning direction of the light source during a goniometric measurement. For this reason, type C motion is preferred for lamps and luminaires, whereas more directional light sources such as vehicle lighting, runway lighting and VMS signs are best measured using a type A or B motion goniophotometer. It is also important to operate the light source in its intended or design orientation during a measurement. If this is not possible, a correction measurement must be performed and applied to the goniophotometer test results.

The importance of performing goniophotometric measurements of lamps and luminaires in the far-field was explained, and guidance given for

determining the limiting photometric distance based upon the luminous aperture of the device under test, but also taking into account the beam angle of the light source. Great care must be taken to ensure that far-field measurements are performed with very narrow angle light sources, the photometric distance for which can be way in excess of the more usual five to ten times ratio of the size of the lamp or luminaire that would be used with wide angle, diffused light sources.

A comparison with integrating sphere measurements reveals that while a goniophotometer can provide a reading of total luminous flux, there are reasons to want to use an integrating sphere as well for routine QA testing, including the faster measurement speed and likelihood of more accurate measurements.

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 international 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](#)