Integrating Spheres:
Theory & Applications

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Key Words

INTEGRATING SPHERE, ULBRICHT KUGEL, DIFFUSE REFLECTANCE, LAMBERTIAN, RADIOMETRY, PHOTOMETRY, HEMISPHERICAL REFLECTANCE, UNIFORM LIGHT SOURCE, HAZE, VEILING GLARE, DEPOLARISATION, REMOVING SPECKLE

Introduction

The integrating sphere is one of the most useful, yet least understood devices used in optical metrology. This paper will explain how the integrating sphere came into existence, what it does, how it works, and how it is used to simplify what would otherwise be complex measurements in fields such as radiometry & photometry, in measuring the optical properties of materials and in the calibration and distortion correction of cameras and image sensors.

Integrating spheres were first introduced in 1894 as a tool to measure the output of electric lamps. Today, integrating spheres are widely used in the measurement of light, as sources of uniform radiance or irradiance for calibrating image sensors, cameras and remote sensing instruments and for testing the optical properties of materials.

An integrating sphere is a hollow, spherical chamber coated internally with a high reflectance coating that exhibits diffuse reflectance. Spheres are used as directionally-insensitive collectors of light when combined with photodetectors. Conversely, an internally illuminated integrating sphere emits a field of spatially and angularly uniform luminance or radiance which is perfect for testing and calibrating imaging systems, detector arrays and remote sensing instruments.

Integrating sphere are commonly used in the following applications, which will be reviewed in this paper:

- Measurement of reflectance (total hemispheric, diffuse and specular components)
- Measurement of haze
- Measurement of veiling glare
- Measurement of total luminous flux from LEDs, lamps and luminaires
- Measurement of total radiant flux from lasers (“laser power meter”)
- Measurement of total integrated scatter
- As a source of uniform luminance or illuminance for testing and calibrating cameras and image sensors
- As a luminance standard for calibrating spot and imaging photometers & spectroradiometers
- As a depolarising device
- As a device to remove laser speckle

The First Integrating Sphere

The integrating sphere (or Ulbricht's Kugel as it is known in its homeland) came into existence in 1894. The invention of the integrating sphere is attributed to German engineer Richard Ulbricht (1849 – 1923) who was responding to the need for a simple device to measure the amount of light produced by electric lamps. A model of Ulbricht's integrating sphere is displayed at the Technical University of Dresden to celebrate his invention.

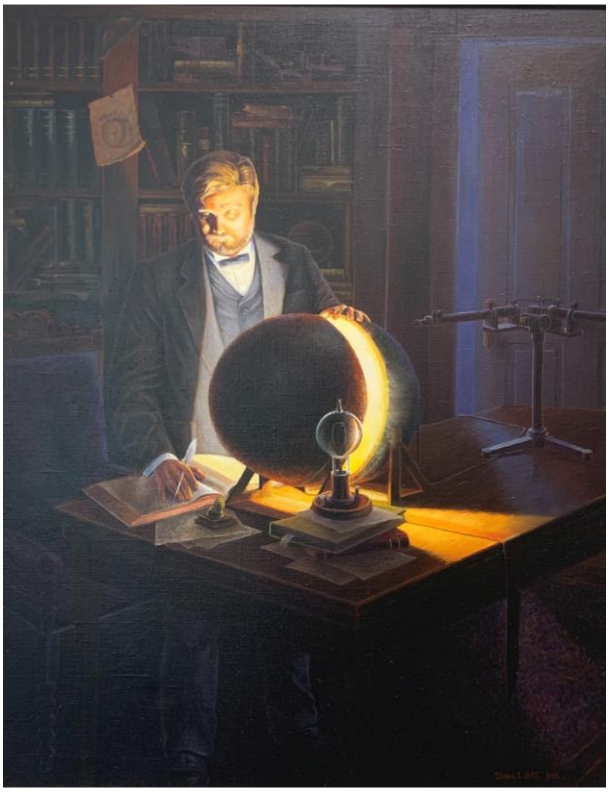

Figure 1: Richard Ulbricht and the First Integrating Sphere (from a Painting Commissioned by Labsphere in 1994, Celebrating the Anniversary of Ulbricht's Invention)

For completeness we should add that the theory of the integrating sphere was first published two years prior. In 1892, the British physicist Dr W E Sumpner (1865 – 1940) wrote a paper on "The Diffusion of Light" in relation to his work on the reflectivity of materials that was published in the Proceedings of the Physical Society of London. So, while Sumpner's work helped to explain the theory behind the integrating sphere, Ulbricht is recognised as having built the first practical example.

Integrating Sphere Theory

In optics, an integrating sphere is a hollow, spherical chamber coated internally with a matte, high reflectance coating. Any light entering an input port on the sphere wall is subjected to multiple, random, omni-directional reflections, such that the resultant radiance or luminance over the surface of the sphere wall is equalised. In other words, the brightness of the sphere wall is the same at all positions. Thus, a photodetector (or spectrometer) mounted at the wall of the sphere and viewing a portion of the sphere wall opposite receives a known proportion of the total light entering into the sphere, regardless of the size or shape of the beam or the direction from which the light came.

The integrating sphere can extend the field-of-view of a photodetector placed at the wall of the sphere to 180° or 2π steradians (solid angle). Thus, the integrating sphere effectively collects a known proportion of all of the light that is emitted from a light source that is either shining into the sphere through a port opening or is placed within the sphere itself. Imagine trying to measure the total light emitted from an incandescent (or any other) lamp with a single 1cm^2 photodiode – it is almost impossible without resorting to moving the detector about the source and determining the total flux as the summation of the directional intensity values. However, simply place the lamp inside an integrating sphere and the signal received onto the photodetector is proportional to the total light emitted from the lamp.

The Perfect Sphere is Perfectly Impossible!

The uniform radiance field that we aim for within an integrating sphere requires that we satisfy four basic criteria: first that the reflective surface is spherical; second, that the surface possesses a diffuse (or matte) – rather than specular (glossy) finish; third, that the surface possesses a high level of reflectance; and fourth that the sphere coating is non "wavelength selective" (reflects all wavelengths equally). Depart from any one of these ideals and the radiance over the surface of the sphere wall will start to vary from one location to another. This is why we don't ever hear about "integrating cubes" – or rather, if we do, they are known to give very poor performance!

We say that the perfect sphere is perfectly impossible because the mere presence of port openings to allow light into the sphere, baffles to screen line-of-sight and ports to mount a photodetector mean that the radiance uniformity is disturbed. We minimise these disturbances by seeking to limit the port fraction to less than 5% of the total sphere wall surface area. We also seek out sphere coatings that are as diffuse as possible, have high reflectance and have a reflectance that is as near constant at all wavelengths as possible.

Integrating Sphere Coatings

Imagine a material which reflects light equally in all directions. It appears equally bright to an observer, regardless of the angle from which they view it. What I am describing is known to optical physicists as a Lambertian reflector. The 18th century Swiss polymath Johann Heinrich Lambert (1728-1777) described the concept of a perfect diffuse reflector in his 1760 book "Photometria". The adjective "Lambertian" has become synonymous with materials that are matte or diffuse. A diffusely reflecting material behaves very differently to a perfect mirror. Instead of all of the light reflecting in the specular direction the light reflects in all directions (Figure 2). For a theoretically perfect Lambertian (or diffuse) reflector, the intensity (defined as the flux per unit of solid angle) of light reflected obeys Lambert's Cosine Law. Mathematically, the decrease in intensity at increasing angle (Lambert's cosine relationship) is perfectly offset by the increasing projected area of the beam (also a cosine relationship), therefore resulting in a constant radiance or luminance over the entire sphere surface.

The level of reflectance is also an important criterion for an integrating sphere coating. The higher the surface reflectivity, the lower the absorption loss per bounce, the more the light bounces around within the chamber, and hence the higher the radiance uniformity. In practice, no material exhibits 100% reflectance, so sphere coatings are chosen that give as high a reflectance as possible, taking into account the cost and also the practicalities of application.

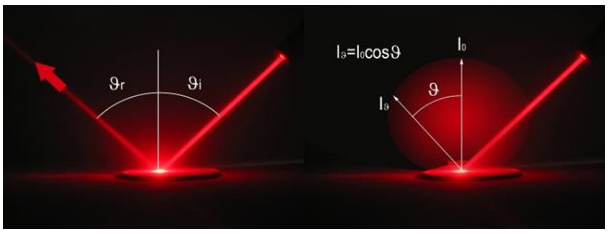

Figure 2: Specular Reflectance Versus Diffuse (Lambertian) Reflectance

The first integrating spheres were coated by "smoking" with magnesium oxide, effectively burning magnesium shavings with a blow torch and allowing the vapour to condense onto the sphere surface. The reflectivity achieved varies with the coating thickness, but a nominal reflectance of 96% at 550nm is typical. It was only after the development of Eastman Kodak's 6080 diffuse white paint (a sprayed-on barium sulphate formulation) in 1968 that integrating spheres started to be routinely deployed in metrology equipment. The reflectance of barium sulphate also varies with thickness, but a nominal reflectance of 98% at 550nm is typical.

Traditional integrating sphere coatings for the UV-VIS-NIR spectral region (250-2500nm) tend to be fragile and easily damaged or optically degraded with exposure to high temperatures or ultraviolet radiation. To address these limitations, American company Labsphere developed an integrating sphere coating called Spectralon in 1986. Being a

sintered form of PTFE (polytetrafluoroethylene), Spectralon is a solid, white thermoplastic that is machined into durable integrating spheres (and other reflectors). Compared to previous sphere coatings, Spectralon is mechanically, thermally and optically stable. Spectralon, and the similar Zenith Polymer material developed by SphereOptics in Germany, achieve the ideal of near-Lambertian diffuse reflectance combined with a high level of reflectance. At >99% in the 400-1500nm band, and >95% from 250-2500nm, the diffuse reflectance is the highest of any material in the UV-VIS-NIR band.

The small incremental increases in reflectance, for example 99% versus 98% for Spectralon (PTFE) versus barium sulphate, may not sound significant, but once you factor in the multiple reflections that occur within the integrating sphere (we call this the "sphere multiplier" effect), it is easy to understand how a Spectralon sphere can have twice the throughput compared to an otherwise identical barium sulphate painted sphere.

Please refer to the charts below which compare the reflectance of Labsphere's Spectralon material with that of Spectraflect, a barium sulphate formulation (Figure 3) and the resultant increase in sphere throughput or radiance gain (Figure 4). The use of Spectralon directly translates into superior sensitivity and enhanced signal-to-noise measurements. The difference in reflectivity increases significantly as you move into the UV or IR regions, and for this reason, Spectralon (or Zenith Polymer) is the sphere coating of choice in advanced reflectance spectroscopy instrumentation.

What of sphere coatings for the infrared? The most common is an electro-plated gold coating that is applied to a roughened metal substrate. Labsphere's Infragold coated spheres have a nominal reflectance of 94% and can be used over the entire near to far-infrared region, spanning 800nm to 20µm.

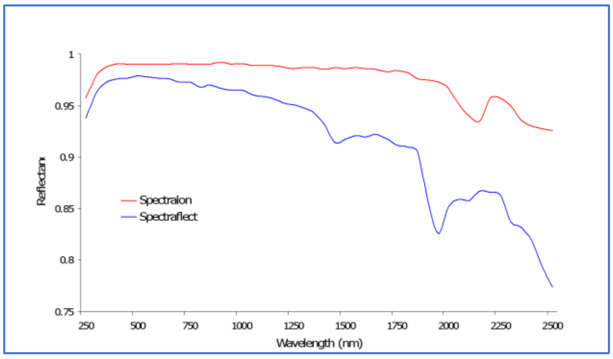

Figure 3: Comparison of Hemispheric Reflectance of Labsphere Spectralon (PTFE) Versus Labsphere Spectraflect ($BaSO_4$) Integrating Sphere Coatings

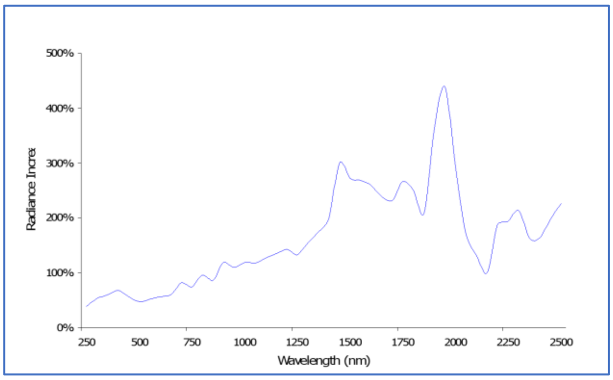

Figure 4: Comparison of Throughput (Radiance Gain) of a Spectralon Integrating Sphere Versus an Identical Sphere Coated with Spectraflect ($BASO_4$)

Coating	MgO	$BaSO_4$	PTFE	Gold
Coating Type	"Smoked"	Spray-On	Monolithic (Machined)	Electro-Plated
Useful Wavelength Range	300-1200nm	250-2500nm	250-2500nm	0.8-20µm
Reflectance	96%	98%	99%	94%

Table 1: Comparison of Common Integrating Sphere Coatings

What Are Integrating Spheres Used For?

Integrating spheres find application in three main areas of optical metrology: in the measurement of the light emitted from light sources (radiometry and photometry); in the measurement of the optical properties of materials (reflectance, transmittance, scatter and haze); and in the testing and calibration of cameras and image sensors, including the spectral imaging instrumentation used in remote sensing applications and aboard earth observing satellites.

One may purchase "general purpose" integrating spheres (Figure 5), but it is usually better to choose a dedicated integrating sphere that has been designed for the type of measurement you wish to make.

Figure 5: A General Purpose Labsphere Integrating Sphere

Radiometry & Photometry

An integrating sphere allows for the measurement of the total light emitted by a lamp, laser, LED or any other light source with "challenging properties", meaning large area or highly divergent beams that would be difficult (if not impossible) to measure using traditional radiometers, photometers or laser power meters.

A wide variety of laser power meters are commercially available based upon thermal or photodiode detectors, but there are specialist applications where an integrating sphere coupled to a photodetector presents unique advantages. These include:

Figure 6: Labsphere LPMS Integrating Sphere Laser Power Meter Radiometer

- Low power lasers with large beam areas, or highly divergent beams. In this case a large thermal detector may lack the sensitivity to measure at low powers, while a more sensitive photodiode meter has a small active area. Combining the photodiode with a sphere gives you a radiometer with high sensitivity but with the ability to collect a large or divergent beam.
- Laser beams with dynamic displacement. Similarly, if the laser beam suffers from dynamic displacement (i.e. it moves around), you will need a larger area detector.
- Applications where you wish to measure high and low powers with the same power meter. In this case, the thermal power meter that you might use to handle the high-power measurement would be unable to also measure much lower powers due to a limited dynamic range. This might be the case when testing the transmittance and damage threshold of laser filters. For this application, you can take advantage of the inherently wider dynamic range of a photodiode detector and the attenuation introduced by the integrating sphere by combining the two

and being able to measure over a 7 or 8 decade dynamic range, versus 2-3 decades with a typical thermal power meter.

The Labsphere LPMS family of laser power measurement integrating spheres (Figure 6) employ a novel, non-radial photodetector position that provides for high attention (e.g. 10,000:1) of the incident laser beam and an insensitivity to a change in the beam direction or divergence over a range of about 85° (Figure 7).

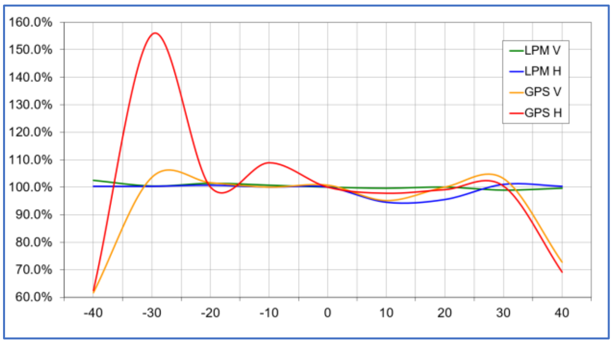

Figure 7: Comparing the Angular Response of a Labsphere General Purpose Sphere (GPS) to that of the Laser Power Measurement Sphere (LPM) - Chart Shows the Uniform Response of the LPM Sphere Over a Wider Range of Angles (±40°, Horizontally & Vertically)

In the field of LED, lamp and luminaire photometry, an integrating sphere photometer is the most common means of measuring total luminous flux (in lumens) as well as colorimetric and colour rendering properties (Figure 8). The device under test is either placed within the integrating sphere (so-called 4π flux measurements) or placed outside the sphere and the directional beam shone into the sphere through a port opening (so-called 2π flux or forward flux measurements). The integrating sphere should be equipped with a so-called auxiliary lamp, which is the means by which the degree of self-absorption of the test source can be determined and a correction applied.

Figure 8: 2m Spectralon-Tiled Lamp Measurement Integrating Sphere Photometer (Courtesy of NPL)

Reflectance Spectroscopy

In reflectance spectroscopy, a light source illuminates a sample held at a sphere port (Figure 9). The reflected component of the radiation irradiates the interior of the sphere, which is again sampled by the photodetector at the sphere wall (or a spectrometer, usually connected to the sphere via an optical fibre). The reflectance of the sample is computed as the ratio of the detector signal when the sample is illuminated compared to the signal when a surface of known reflectance is illuminated (known as the “reflectance standard”). Without the sphere, one would only measure the directional component of reflectance or transmittance and not the total.

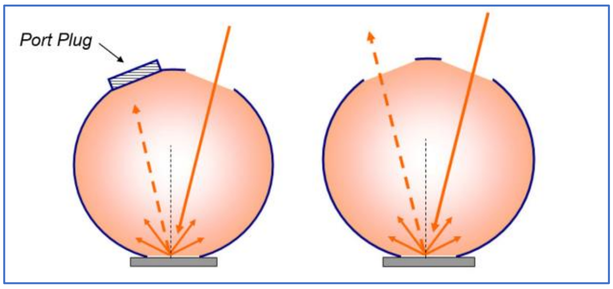

Figure 9: Integrating Sphere Configuration for Reflectance Measurements, Total Hemispherical (Specular-Included) on the Left and Diffuse Only (Specular Excluded) on the Right

For reflectance measurements, there are a number of sphere configurations commonly used. The traditional approach, which is employed in "high-end" scanning spectrophotometers, is to illuminate the sample with a collimated beam of tunable, monochromatic light, and to collect the reflected light hemispherically using the integrating sphere coupled to a broadband photodetector. As the wavelength of the monochromator is tuned, the reflected signal is recorded at each wavelength. This measurement geometry is described as directional illumination with diffuse collection. The angle of illumination of the sample with respect to the surface normal is usually between 0-10°, the most common being 8°. For simplicity, a reflectance measurement performed with 8° illumination and total hemispherical collection using a sphere is given the notation "8°/H".

The reflectance integrating sphere can be equipped with a so-called "gloss trap". This is either a port opening, or highly absorbent chamber positioned on the sphere wall so as to exclude or absorb the specular component of the light reflected from the sample. With the specular port open, or fitted with a gloss trap, the light that remains within the integrating sphere is the diffuse-only component of reflectance. The notation "8°/D" is used for this measurement condition. It follows that if one were to measure the 8°/H hemispherical reflectance and then subtract the 8°/D diffuse reflectance, the magnitude of the specular reflectance at 8° could be computed. One refers to the measurement of specular-included versus specular-excluded reflectance.

Camera & Image Sensor Testing

In the field of image sensors, cameras and the specialist multispectral and hyperspectral imagers used on satellites or in remote sensing applications, the output of an internally illuminated integrating sphere provides a spatially and angularly uniform radiance field that can be used to both impart an absolute radiometric calibration onto the sensor and to correct for image distortions and sensor non-uniformities (Figure 10).

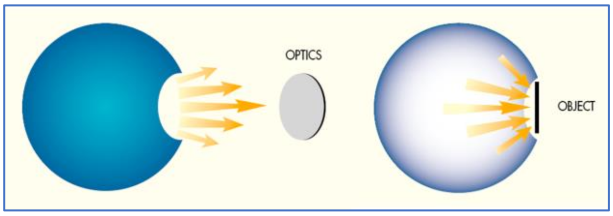

Figure 10: An Internally Illuminated Integrating Sphere can be used as a Source of Uniform Radiance or Uniform Irradiance

In the previous applications, the integrating sphere is used as a collecting device for the measurement of radiant flux, either the absolute amount emitted from a light source itself or the relative amount of flux transmitted or reflected by materials. The open port of an internally illuminated integrating sphere can itself serve as a large area diffuse light source. Lamps are placed either inside the integrating sphere around the perimeter of the viewing port (exit port), or placed outside but shining in. The lamps are usually baffled from the exit port of the sphere.

Multiple lamps can be used to increase the radiance as well as provide a step-wise method of attenuating the radiance level. Tungsten halogen lamps are most commonly used with integrating sphere sources, and are operated at a constant current to maintain their colour temperature. These lamps provide a continuous spectrum, free of emission lines or temporal instability when operated from a current regulated power supply. The output from an incandescent lamp is however quite weak in the blue part of the spectrum, so to deliver higher colour temperatures, or to match a particular solar (Air Mass) spectrum, the output from a discharge lamp can be added, with the integrating sphere spectrally mixing the two sources.

More recently, uniform light sources are being offered that use LED light engines, such as the

SpectrALL range of sources from Labsphere (Figure 11). These contain an array of LEDs, each with a different peak wavelength. By driving each LED in the array at the appropriate current, it is possible to create a source of uniform radiance that is either colour and/or spectrally tunable.

Figure 11: Labsphere SpectrALL Tunable LED Uniform Light Source

Uniform Irradiance Applications

Focal-plane sensor arrays (FPA) are multi-element photo detectors used in electronic imaging products. There are various types of FPAs, such as charge-coupled devices (CCD), charge-injection devices (CID), complementary metal-oxide semiconductors (CMOS), and photodiode arrays (PDA).

Once fabricated and packaged, the devices can suffer from some degree of non-uniform gain and offset coefficients. When exposed to an equal irradiance of light, each pixel in the array does not produce an identical electrical signal. Photo Response Non-Uniformity (PRNU) is due to differences in responsivity (gain) among the pixels in the array and Fixed-Pattern-Noise (FPN) is due to variation in dark current (offset). In the presence of gain and offset variations, the device produces images that have features that do not exist in the original object but are imparted on the image by the array. In other words, a picture of a uniform field is not uniform.

Pixel gain and offset normalisation can be easily accomplished using an integrating sphere as a source of uniform irradiance. Offset normalisation is simply performed by providing zero irradiance on the array and setting the output signal of each pixel to zero. During gain normalisation, a uniform source produces irradiance on the array that is equal at each pixel. The gain, or responsivity, of each pixel is set so that each pixel produces an equal electrical signal. Linearity can be measured by irradiating the array with varying light levels and measuring the signal produced.

Uniform irradiance is produced by placing the FPA at the exit port of a uniform source sphere. At the exit port, the array will be uniformly lit but irradiated from all directions. If a limited field is desired, the array can be located some distance from the exit port. This distance, and the size of the exit port must be chosen to provide the required field angle and to ensure adequate uniformity.

The uniform light source can also be used to determine the responsivity, dynamic range and linearity of an array. By introducing narrowband light of various wavelengths, the spectral response can also be measured.

Uniform Radiance Applications

Digital cameras, spectral imaging systems, and other electronic imagers must be normalised in much the same way as bare FPAs (Figure 12). However, one more element is introduced that must be accounted for — the optical imaging system. Imaging systems, whether they be refractive, reflective, or both (catadioptric), suffer from distortions that vary with field angle. The most common are lens vignetting and the cosine-fourth intensity drop-off to the edges of the field of view. A procedure similar to that described for simple FPAs will correct for cosine-fourth fall-off and other sources of irradiance variation in the image.

Figure 12: Integrating Sphere as a Source of Uniform Radiance Being Used for Correcting a Camera Image

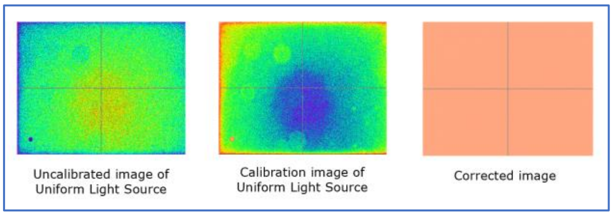

Figure 13: Camera Distortion Correction

Correcting the imaging performance of a camera or imaging system requires that the integrating sphere serve as a source of uniform radiance (as opposed to irradiance as required for a bare detector array). The output of an integrating sphere uniform light source is characterised both by its spatial as well as its angular uniformity.

As shown above (Figure 13), the uniform source sphere presents a field of uniform radiance to the camera, but due to the image distortions that arise from both the lens and from the image sensor, the raw image reveals numerous nonuniformities (left picture). The distortions are corrected simply by viewing the exit port of the sphere and recording a slightly defocussed calibration image (middle picture) of the rear wall of the sphere opposite the exit port. The calibration image is simply the inverse of the raw image of the sphere port. By multiplying the raw image by the calibration image, we arrive at the corrected image (right picture).

Other Applications

In addition to the aforementioned applications, intenrating spheres are also used in the measurement of haze, veiling glare, total integrating scatter and for depolarizing a light source.

An integrating sphere can be configured for both diffuse reflectance as well as for diffuse tramsittance measurements. In transmittance mode, the sample is placed at the input port of a sphere which is illuminated by a collimated sample beam (Figure 14, left picture). Both the scattered (diffuse) and regular components of transmittance are captured by the integrating sphere and the total transmittance of the sample recorded.

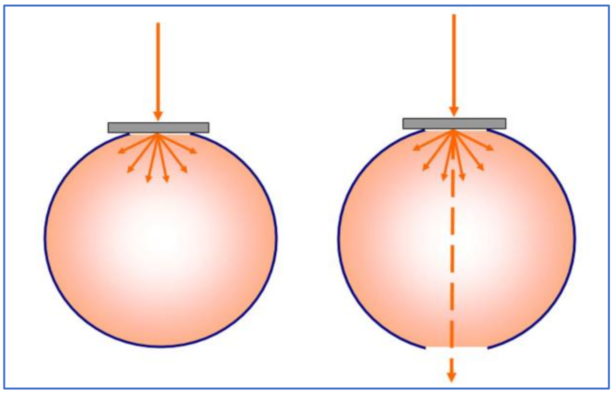

Figure 14: Measuring Diffuse Transmittance & Haze

Haze is a special type of transmittance measurement, whereby we measure just the diffuse component of transmittance (Figure 14, right picture). The regular component of transmittance is rejected through a port opening opposite the input port (or into a light trap), leaving just the diffuse component of transmittance to be measured. The size of the light trap or port opening is carefully chosen to reject both the specular (regluar) beam and a portion of the near-specular scattered light.

Veiling glare is that light that reaches the image plane as a result of scatter within an optical system, for example light reflecting from the interior surfaces of a multi-element lens. Measuring veilling glare requires an integrating sphere that is equipped with an internal lamp that provides for diffuse, hemispheric illumination of the lens under test that is placed at the exit port (Figure 15). On the rear wall of the sphere opposite the sample (exit) port is a black light trap. A camera views the image plane of the lens through a pinhole and the veiling glare (or veiling glare index) is computed from the amount of light recorded by the camera that enters the black area in the image.

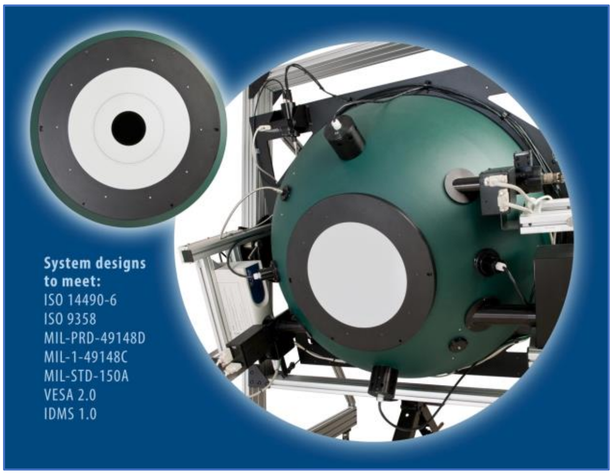

Figure 15: Integrating Sphere for Measuring Veiling Glare

Total integrated scatter (TIS) is simple another name for the diffuse component of transmittance, so requires an integrating sphere with light trap (or port opening) opposite the sample port to reject or absorb the regular (or specular) component of transmittance.

An internally illuminated integrating sphere acts as a source of uniform luminance. If the sphere output is calibrated, that calibration can be transferred into a spot luminance meter or spectroradiometer that views the exit port on the sphere. Similarly, a uniform light source can be used to both correct for image distortions and transfer an absolute calibration into an imaging photometer or colorimeter.

The random nature of the reflections within an integrating sphere can be exploited to depolarise a light beam. For a linearly polarised incident beam, the integrating sphere will almost completely depolarise the light.

Finally, to the question of removing speckle (transverse coherence interference) in a laser beam (Figure 16). Rather counterintuitively, an integrating sphere does not reduce the appearance of speckle in a laser beam shone into the sphere. However, by mounting the sphere on a vibrating platform, the speckle is almost completely removed.

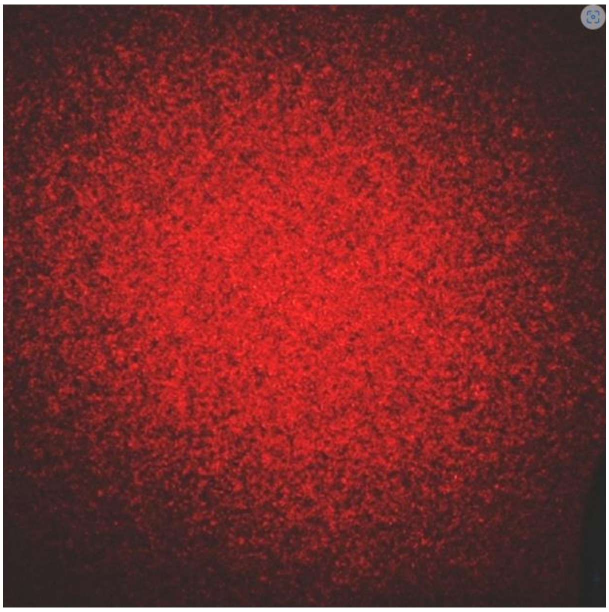

Figure 16: Speckle is an Interference Pattern Resulting from Transverse Coherence in a Laser Beam (Courtesy of Wikipedia)

Further Reading

Pro-Lite is the parent company of SphereOptics GmbH and also serves as the distributor for Labsphere Inc, and supplies integrating spheres, light metrology instrumentation, and calibrated diffuse reflectance standards and targets on behalf of both companies.

Pro-Lite also supplies instruments for measuring reflectance and BRDF/scatter from Avantes (spectrometer systems), Surface Optics Corp (reflectometers) and from The Scatter Works (scatterometers).

Pro-Lite Integrating Spheres

Pro-Lite Reflectance Standards

Pro-Lite Spectrometers

Pro-Lite Scatterometers

Surface Optics Reflectometers

In addition, Pro-Lite also provides independent measurement services for scatter (BRDF/BTDF), as well as spectral reflectance and transmittance (250-2500nm and 800nm-15µm), the latter being accredited to ISO 17025.

Pro-Lite Measurement Services