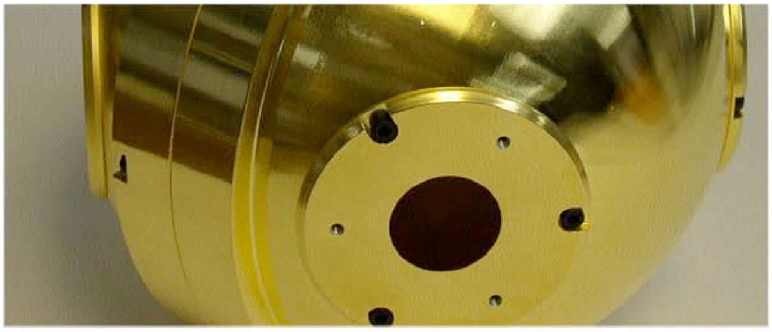
Integrating Sphere Design and Applications



TECHNICAL

INFORMATION

SphereOptics

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1.0 Integrating Sphere Theory

The following section discusses of the theory and technical background of integrating sphere performance.

1.1 Materials and Spheres:

An integrating sphere in essence is an enclosure to contain and diffuse input light so that it is evenly spread over the entire surface area of the sphere. This diffusion is completed through two mechanisms: a lambertian reflectance surface (or coating) and a geometrical sphere shape. A Lambertian reflectance surface is a physical ideal – 100% reflectance and completely uniform angular spreading of the light energy on the first bounce. Or, to restate this theory, as illustrated in Figure 1, the intensity from the incident radiation I_0 varies only as the viewing angle of the surface θ. When this ideal Lambertian surface is combined with a spherical enclosure as in Figure 2, the geometry of the sphere ensures that every point within a sphere receives the same intensity or light as every other part of the sphere at the first bounce. Coincidently, all angular properties of the intensity also drop out.

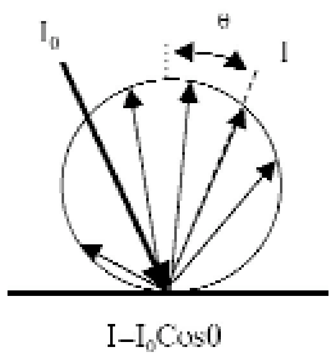
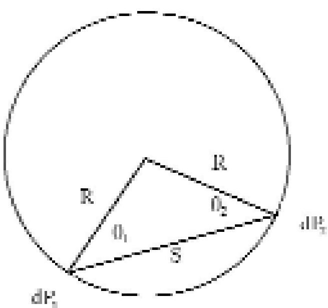


FIGURE 1:
Lambertian Surface



$$Flux(from dP_1 to dP_2) = \frac{\cos\theta_1 \cos\theta_2}{\pi S^2} dP_2$$

$$= \frac{\cos\theta_1 \cos\theta_2}{\pi(2R\cos\theta_1)(2R\cos\theta_2)} dP_2 = \frac{dP_2}{4\pi R^2} = \frac{dP_2}{A_{surfacearea}}$$

FIGURE 2:
Radiation Exchange within a Sphere Enclosure with a Lambertian Surface Area dP_1 to Surface Area dP_2

Therefore the light incident into an integrating sphere is, in theory, spread evenly and without angular distribution over the entire surface of the sphere.

1.2 Sphere Radiance:

From the above expressions, one would expect that the energy from the first bounce illuminating every other spot on the sphere would be simply ϕ_{in} / A_s , or the input energy (ϕ) divided by the surface area of the sphere. Since an illuminated surface is also a reflective, radiance source, the expression of radiance at each spot on the sphere after the first illumination would be as follows:

Eq. 1: Radiance of a Reflective Surface:

$$L_{Surface} = \frac{\phi_{in}\rho}{\pi A_S}$$ (Typical Units: W/m^2*sr)

Where ρ is the reflectivity of the sphere wall and π is the total projected solid angle from that surface. Now that each spot is reflective and radiating, there are multiple reflections within the sphere enclosure. Consequently, each spot can expect to be illuminated many more times than just that first bounce. The radiance of the sphere wall at any point within the sphere is given by the following relationship that is attributed to the multiple reflections within the sphere chamber:

Eq. 2: Radiance of the Sphere Wall:

$$L_{Sphere} = \frac{\phi_{in}}{\pi A_s} * \frac{\rho}{1-\rho(1-f)}$$ (Typical Units: W/m^2*sr)

We see that the reflectivity factor increases the sphere throughput in an asymptotic fashion and actually provides a unit-less gain factor to make the sphere radiance better than the original case of single surface illumination given in Equation 1. We also see that there is an additional modifying (and attenuating) term in the equation of (1-f). This is the factional area from the surface area of the sphere (expressed as a percentage) that is taken up by non-reflective surfaces (ports, detectors, etc) or Port Fraction, f. These non-reflective features subtract from the ideal throughput of an integrating sphere as they represent losses in the enclosure's multiple reflection effects. It is important to calculate these static feature effects into the throughput.

2.0 Designing and Using and Integrating Sphere – practical considerations

The general radiance of the sphere wall expressed in Eq. 2 is a useful general expression for trying to estimate actual performance of real sphere. There are several factors which are derived from this equation that deserve discussion with regard to “real” vs. theoretical sphere performance

2.1 Sensitivity:

Embedded in Eq. 2 is the sphere multiplier

Eq. 3: Sphere Multiplier (sensitivity factor): $$M = \frac{\rho}{1 - \rho(1 - f)}$$

This is a number greater than one; typically M is in the range of 10 to 25 for most real spheres. The ρ factor is an asymptotic relationship; specifically as ρ approaches 1 the M factor becomes larger until it approaches infinity. One can see this means that a 0.99 factor has a much bigger multiplier than 0.80. Naturally, from a throughput concern the ρ factor should be as large as possible to have a large multiplier. However, the higher the ρ factor, the more “sensitive” the sphere will be to changes in the reflectivity of the sphere. In practical terms, if a small amount of dust gets in a high reflectivity sphere, the throughput can change by quite a bit. Generally, we only see this effect move in a down ward throughput direction, the sphere’s reflectivity never improves over its initial pristine state. So you can expect your sphere’s throughput to gradually decrease over time depending on your ability to keep the interior of the sphere clean.

One practical reaction to this sensitivity issue is to try to reduce the effect by lowering the sphere reflectivity so the multiplier is reduced. The lamp industry typically uses 80% coating to this effect (M = 4 vs. M = 50). However, there are two very detrimental effects of this tactic – severely lowered throughput (again proportional to the M factor ratio 4:50) and a reduction of the “integration” power of the sphere.

Multiple reflections are necessary for a sphere to be able to spatially make each point receive the same number of illuminations. So, intuitively, another derivative of M is an indication of the number of reflections in the sphere. M increases because the overall number of times photon can bounce before being extinguished is increased because the reflectivity is increased. When M is lowered, the sphere looses in-power to “average out” or integrate the light intensity at each point because the number of illuminations at each point is less. This lower M means the sphere is more prone to spatial non-uniformities in the sphere: baffles, shadows, directional sources, ports, etc. Therefore, a sphere with M = 4 (80%) would have 12.5 times less relative integrating power than an M = 50 (99%).

2.2 Port Fraction:

One important factor ignored so far in Eq. 3 is the (1-f) port fraction in the denominator. The port fraction of the sphere's throughput. "f" is the fractional percentage of the surface area in the sphere taken up by ports, detectors, and other non-reflective surfaces. "f" has a more limited effect on the overall throughput of the sphere; however, f should not be larger than 5% for good integrating sphere performance. Typically this effect is noticeable by small compared to M effects: 2-10%. The most pronounced effect is when an open or closed port is introduced to a sphere with a "known" throughput. Countering this effect is usually fairly simple, for instance, an open port is essentially "zero" reflectivity, so to emulate this effect with a plug a low reflectivity coating can be used on the plug (e.g. a "black" port plug).

For some cases, port fraction can be the most insidious factor in measurement. For example, when a shiny metal laser diode sub-mount is brought up to the input port of a sphere for measuring total power of the diode, the reflectivity of the sub-mount adds a few percent to the sphere throughput due to is port fraction contribution. However, unless you knew this was going to happen, or base-lined (calibrated) the sphere with that particular sub-mount in place, the effect would be invisible to you and your power reading will be too high. In this case, the effect can be minimized or eliminated by painting the sub-mount black or using a black mask in front of the sub-mount.

2.2.1 Auxiliary Correction for Port Fraction Effects:

In an alternate method of compensation for port fraction offsets, a sphere can be baselined for two different port fraction conditions. This method is commonly referred to as auxiliary correction and it requires have a secondary stable light source on the sphere other than the source to be measured. In the laser example given in Section 2.2, the secondary, or auxiliary source (probably another laser for best case) could be turned on first for an open input port condition and then second for the port with the sub-mount in place. The resulting differential between these two measurements (in percent) would be the resulting difference in the sphere for that particular sub-mount (as long as the light source is considered stable between these two conditions). This auxiliary correction procedure is valid for monochromatic or broadband sources and is commonly used in lamp measurement conditions to compensate for sockets and lamp types in a sphere.

2.2.2 Port Fraction effects in Reflection Measurements - Substitution Effects:

Another natural effect of port fraction has commonly been called "Substitution Effect" and it has to do with using spheres to make reflection measurements.
More information can be found in Section 4 on Reflection Measurements. Typically, a reflection measurement is done by illuminating a sample on the sphere wall with a light beam and reading a detector's response. This measurement usually has two steps: (1) Measure a sample of "known" reflectivity and record the "baseline" of detector, and (2), substitute an unknown sample at the same port and record new detector reading. The reflectivity factor is determined from the percentage ratio of step (1) and step (2). "Substitution Error" creeps into this measurement when the sample (1) and sample (2) have very different reflectivities. This is because the port fraction's affect in the sphere changed when the samples were substituted – again, an insidious error in the measurement. Using samples and references that are approximately of the same reflectance can minimize substitution effects. Other methods for substitution correction methods are given in Section 4.

2.3 Size of Sphere:

The size of the sphere has a great effect on the throughput of the sphere and its integration ability. In Eq. 2, the A_S factor is the surface area of the sphere so the sphere throughput will vary inversely with the surface area – as the sphere gets larger the throughput decreases and visa versa. For simplistic relationships and estimates, the following equation holds true for spheres with equal port fractions:

Eq. 4: Throughput Vs. Sphere Size:

$$Gain / Loss = \frac{(Diameter_{Sphere1})^2}{(Diameter_{Sphere2})^2}$$

In general the sphere size also contributes to the relative integration ability of the sphere. While this is not a directly quantifiable relationship, and intuitive example can be made of a very small 1" sphere vs. a larger sphere 10". The optical path of a photon bouncing in a small sphere is more limited and therefore scattering patterns are more limited. In other words, the small sphere spatial effects are in closer proximity to each other and therefore can have influence over other each other. In a 10" sphere, there is much more spatial spread of energy and more random paths for the photons to follow – therefore energy from any one particular area of the 10" sphere is less likely to have any more or less effect that energy from any other portion of the sphere. Therefore, the chance of "proximity" affecting integration of the sphere energy diminishes as the surface area increases or, overall integration is better for larger spheres.

2.4 Size of Ports in Sphere:

There are two general rules of thumb concerning sphere port size: 1) for general purpose spheres, trying to keep the port fraction $<5\%$, and 2) for luminance/radiance sources, trying to keep the port to sphere ratio less than 1:3. The size and number of ports in a sphere directly affect the port fraction of the sphere. To attain an $f = 5\%$ a sphere would need to be designed with few large diameter ports, or many smaller diameter ports. Using the 1:3 ratio of the maximum port diameter to sphere would also closely follow the 5% rule. With luminance/radiance sources, where uniformity at a port is to be maximized, the 1:3 rule is essential to achieve 98% or better uniformity, radiance or luminance over the entire port surface. In general, ports that exceed this ratio will diminish the uniformity of the sphere and have a great effect on throughput.

2.5 Baffles:

Baffles are one of the most "double-edged" aspects of integrating spheres. In general, baffles are meant to block direct light from one part of the sphere to another. But, in solving a directional light problem with baffle placement, you may create another, like unintentional shading or gradients from the baffle. Typically, baffles are used to prevent a light source or other radiance source - like a wall reflection from a first strike laser – from reaching another area of the sphere with "un-integrated" light rays.

2.6 Time Constant:

Spheres exhibit a time constant in their response to input photons. This effect is due to a lag time or statistical spread in the amount of time it takes photons to travel random paths and reach a given point in a sphere (like a detector active area). The effect looks very much like a RC circuit function with an exponential decay and rise times for a given input pulse. Typical 1/e rise and decay times for most spheres are in the range of 5-20 nanoseconds, but this factor varies with the diameter of the sphere and reflectivity of the sphere wall.

Eq. 5: Sphere Time Constant: $$e^{\frac{-t}{\tau}} \Leftrightarrow \tau = -\frac{2}{3} \cdot \frac{Diameter}{c(light)} \cdot \frac{1}{\ln \rho}$$

This means that typically, the sphere will start to distort pulsed signals with frequencies greater that 50MHz. One other interesting application is that the sphere can actually slow down very, very fast pulses < picoseconds by spreading the signal over time due to the time constant.

2.7 Throughput:

One of the most useful estimations for a sphere system is to try to predict what kind of a signal actually gets a sensor or port for a given input of light. This estimation is usually no better than 2x the actual resulting throughput, but it does provide a rough order of magnitude number to work with. There are three different common scenarios for the sphere presented below.

2.7.1 With an Open Port

The throughput of a sphere at a given port is a simple factor of relating the radiance equation from Eq. 1 to the port size in question:

Eq. 6: Throughput at a Port: $$T_{Port} = \frac{\phi_{in}}{\pi A_s} * \frac{\rho}{1 - \rho(1 - f)} * A_p * \Omega$$

Ω in this case is equal to π Steradians (or 180° full hemisphere: 90° half angle as applied to Eq. 7) and A_p is the area of the port in question.

If the output angle of the sphere is restricted, or a sensor with a defined field of view is looking into the sphere then the solid angle of the angle in question must be applied to the equations in Eq. 6 and 7.

Eq. 7: Solid Angle Estimation: $$\Omega = \pi \sin^2 \theta$$

Where θ is the half angle of field-of-view of the system.

For a given reflectance coating, ρ and sphere size A_S, typical ranges for throughput of this equation range from a 5% to 50% and vary directly with the size of port chosen.

2.7.2 With Detector

The throughput of a sphere with a detector at a given port is a similar effort but in this case we must account for the solid angle defined by the detector field-of-view, Ω (per Eq. 7), and the active area of the detector, A_d:

Eq. 8: Throughput at a Detector:

$$T_{Detector} = \frac{\phi_{in}}{\pi A_s} * \frac{\rho}{1-\rho(1-f)} * A_d * \Omega$$

For a given reflectance coating, ρ and sphere size A_S, typical ranges for throughput of this equation range from a 10e-2 to 10e-6. This estimate varies greatly with the active area and field-of-view of the detector.

For a radiance imaging system (camera or a detector with a lens) it may be more appropriate to use a solid angle estimated from the F-Number of the optical system.

Eq. 9: Solid Angle Estimation For f/#:

$$\Omega = \frac{\pi}{(2 * f/\#)^2}$$

2.7.3 With Fiber

The throughput of a sphere with a detector at a given port is a similar effort, but in this case we must account for the solid angle defined by the numerical aperture (NA) of the fiber (per Eq. 7), the reflectivity of the fiber face, and the effective core diameter of the fiber, A_f:

Eq. 10: Throughput to a Fiber:

$$T_{Fiber} = \frac{\phi_{in}}{\pi A_s} * \frac{\rho}{1-\rho(1-f)} * A_f * (1-R) * \Omega$$

Eq. 11: Solid Angle Estimation for Fiber NA: $\Omega = \pi (NA)^2$

For a given reflectance coating, ρ and sphere size A_S, typical ranges for throughput of this equation range from a 10e-4 to 10e-9. This estimate varies to the greatest degree with the effective fiber core diameter and to a lesser extent with the numeric aperture of the fiber selected.

3.0 Applications - Sphere Configuration Guide:

The following top-down view diagrams have been provided to allow the user to visualize the use of accessories and spheres to meet common integrating sphere applications.

LEGEND

Plug or Spectral	**Plug**
Detector	**Lamp or Light Input**
Plug or Light Trap	**Test Sample**
Reference Sample	**Sample Holder**
Installed Baffle	**Source Diode/LED/Lamp**
Directional Source	**Diffuser**

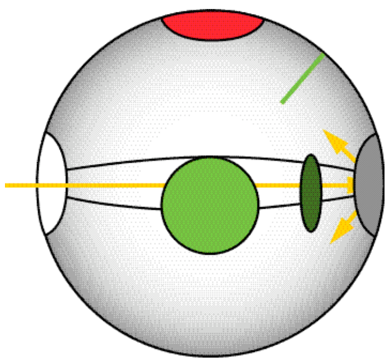


FIGURE 3:
Collimated Power Measurement

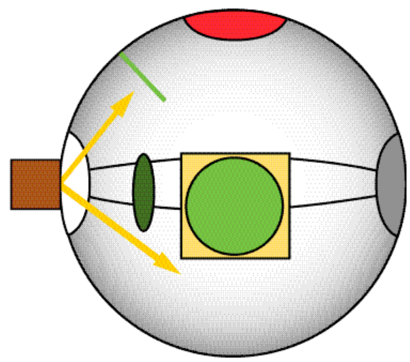


FIGURE 4:
Divergent Power Measurement (angles <+/-15°)

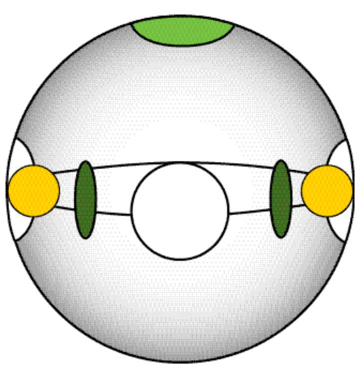


FIGURE 5:
Uniform Source (1 or 2 Sources)

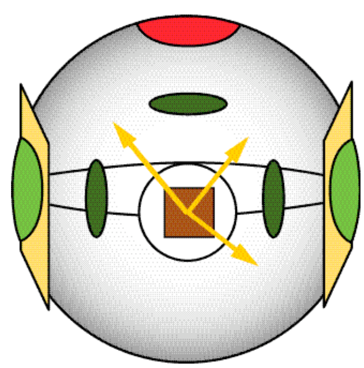


FIGURE 6:
(3) Detector Power Measurement

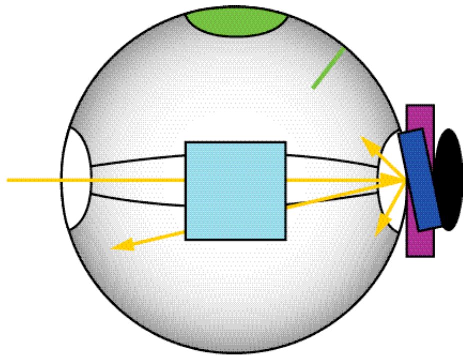


FIGURE 7:
Reflectance Measurement (8°/D)

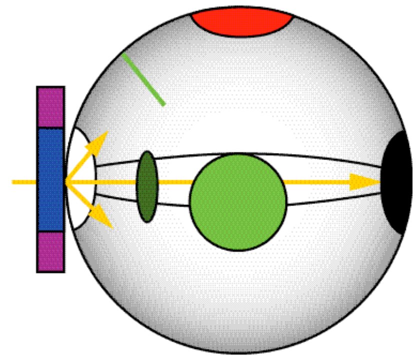


FIGURE 8:
Transmission Measurement

4.0 Application Descriptions

There are a number of common applications for spheres that require some explanation for proper configuration and use of general purpose spheres. This section gives an overview of the nuances of specific measurements; it is not a comprehensive guide to measurement techniques. If specific questions arise, please contact SphereOptics for technical assistance. Use the Legend given in Section 3.0 to understand the sphere diagrams given below – all diagrams are top-down view unless otherwise noted.

4.1 8°/Diffuse Hemispherical Reflectance - Specular Included:

8° Incident Beam /Diffuse collection hemispherical reflectance measurements are a natural application of integrating spheres and can easily be set up with general purpose spheres. An 8° sample holder is used to make any specular beam reflection come off at a near normal angle so they strike the way of the sphere and are included in the sphere measurement. A light trap is sometimes used behind the samples to exclude background for translucent samples.

4.1.1 8°/Diffuse Comparison Method:

One method is called "comparison" and it involves having both the sample and reference on the sphere at the same time. Position of the sample and reference are switched between two measurements to allow each item to be in the incident beam, but both samples never leave the sphere. Having both sample and reference on the sphere at the same time maintains the integrating sphere's port fraction and will minimize substitution concerns. The diagrams below illustrates the technique:

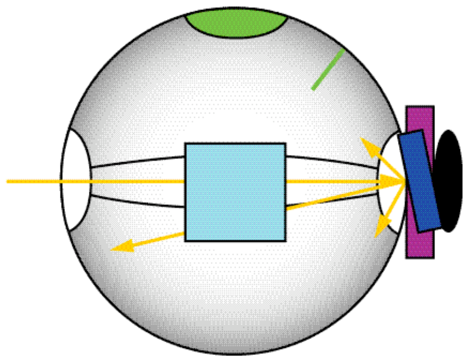


FIGURE 9:
Reference in Beam

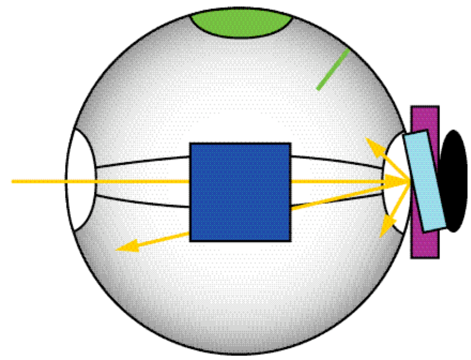


FIGURE 10:
Sample in Beam

4.1.2 8°/Diffuse Double Beam Method:

The most accurate method for overcoming substitution effects is to use the comparison method sphere, but use two identical separate input beams – one incident for the sample and one for the reference. The readings from the detector are recorded for each separate beam with no physical switching of the sample and reference place ment. This technique is used for high-end spectrophotometers that use a chopped beam that is flipped from the sample to the reference via a mirror system – this single beam switch minimizes the possibility of energy differentials between two separate source beams. This technique would require five ports in the sphere – adding an input port diametrically placed from the second sample holder position. A second source would also be added as noted below:

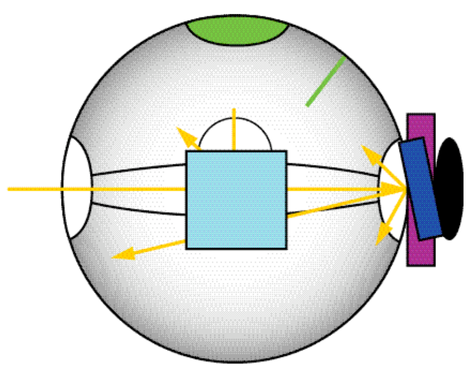


FIGURE 11:
Double Beam Reflectance

4.1.3 0°/Diffuse – Specular Excluded Measurements

An 8° sample holder is used in most cases for specular-included measurements, but if a 0° sample holder is used specular reflections will reflect back out the input port and be naturally excluded from the measurement. This geometry allows the user to make a distinction between "diffuse" reflection (matte) and specular reflections (glossy) for a single sample. The geometry is identical to the reflectance measurement in Section 4.1.1, but uses a 0° sample holder:

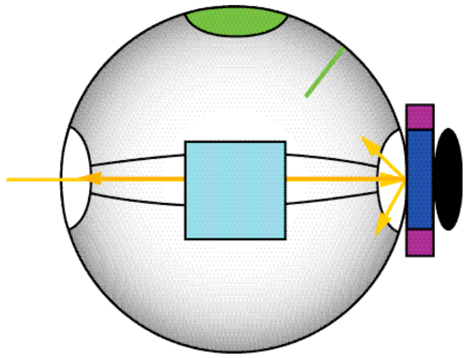


FIGURE 12:
Reference in Beam

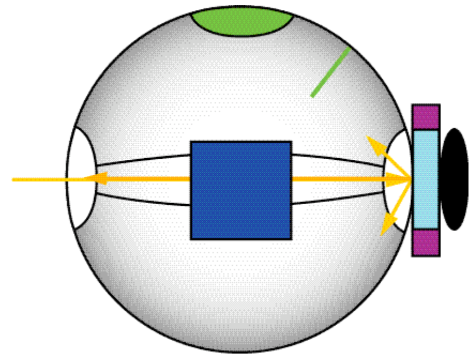


FIGURE 13:
Sample in Beam

If the user switches between a 0° and an 8° holder, gloss and matte components can be identified for a given sample from the difference in these measurement results.

4.2 Transmittance:

Transmittance measurements can be accomplished very easily with a sphere using a similar ratio technique to reflectance. The reference for most transmission measurements would be open air (100% transmittance) or an empty sample container (cuvette, slide plate, etc.). A beam is passed through the sample and into the sphere as in the following diagrams:

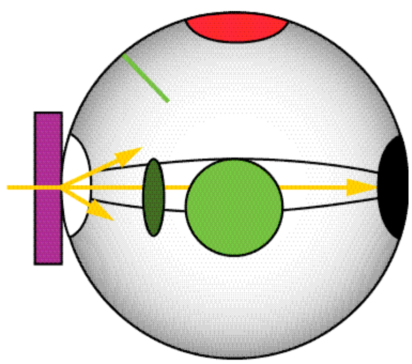


FIGURE 14:
Reference Measurement

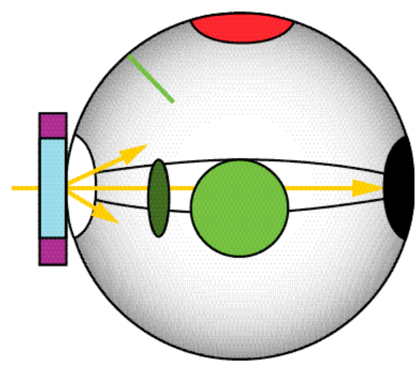


FIGURE 15:
Sample Measurement

Substitution correction can also be an issue for transmittance measurements and a similar comparison or double beam method could be applied to these cases. A light trap placed at the diametric port across from the sample can be used to exclude "normal incidence" (specular) beam transmission. The light trap technique is sometime called a "haze" characterization as it is looking at the diffuse scattering transmission only.

4.3 Center Mounted Sample Reflectance/Transmittance Measurements:

In some cases it is necessary to make center mounted sample measurements. This geometry can allow the sample to freely rotate in the center of the sphere for angular reflectance, transmittance or absorption characterizations. These measurements are extremely complex as the sample is now inside the sphere and its “self absorption” now must be taken out of the measurement. Contact your SphereOptics applications engineer for assistance and further information about these measurements. A center mount sample holder accessory is available for this type of measurement (for ports > 1”) – a typical geometry is provided below for reference (side view of sphere):

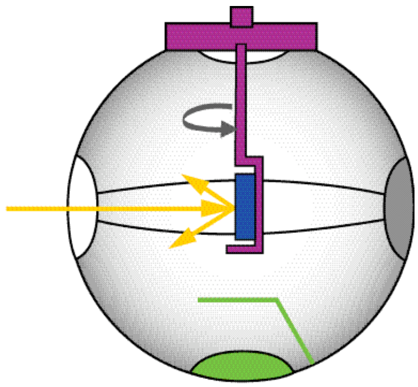


FIGURE 16:
Center Mounted Sample Set-up

4.3.1 Quantum Efficiency:

Another fundamental use of the sphere is to characterize the total energy out of small emissive samples (< 1”) such as an organic LED, light panel or LCD. These devices may be activated either electrically or optically (laser incident energy on sample). The sphere collects the energy from 4π steradians and if the sample’s self-absorption or physical reflective properties can be subtracted from the measurement a total optical efficiency, or quantum efficiency can be calculated for that device. The steps in this measurement vary substantially for electrical samples and samples that are stimulated by an optical source. The set-up for this of measurement is very similar to the arrangement pictured above in Figure 16.

4.4 Laser Power Measurement:

One of the most useful aspects of an integrating sphere is its ability to measure the total flux from optical sources regardless of the spatial geometry of the source. One of the most direct applications of this property is the measurement of laser sources of all types. Additionally, due to the uniform radiation distribution in the sphere multiple detectors can be used at the same time to measure different properties of the same laser – the most common application of this benefit is to use a spectrometer and a power detector at the same time. SphereOptics produces a specific laser measurement sphere design that is optimized for most laser source types and multiple detectors. However, with care, a general purpose sphere can make similar measurements. The following sections outline various geometries that are needed for different laser types. The following section discusses various sphere geometries used for a variety of laser types. We do not discuss the geometry for measuring high divergent laser sources in this guide, as this requires a rather lengthy discussion and special sphere design. We discuss the common applications that utilize a general-purpose sphere design. Please refer to our Technical Note entitled - “Integrating Sphere Laser Power Measurement - A Guide to Sphere Design Considerations for Measuring High Divergent Laser Sources.”

4.4.1 Collimated or Narrow Beam Sources:

Collimated or narrow beam lasers (< +/-15° full angle beam divergence) of lasers present a fairly simple application of general purpose sphere designs. If the source has a well defined beam, the user does not have to worry about incoming light, but rather focus on the spot where the detector first strikes the sphere wall – commonly referred to as the first strike area or virtual source area. Typically, a baffle is placed between the first strike area and the detector(s) on the sphere.

Proper placement of baffles prevents light from directly reaching the active area of the detector, but the area of the sphere wall that the detector “sees” is also of concern – this area is referred to as the virtual detector or field-of-view of the detector. The divergence of the light source should not intersect with this area, as the detector will “see” this first strike radiance as a false high reading. The detector also must not directly view “features” in the sphere like baffles or seams. Usually, there are two options for choosing a functional detector field-of-view: (1) narrow the detector field-of-view to eliminate overlap with any first strike radiance, or (2) place a cosine-receptor (diffuser) in front of the detector active area – the diffuser “averages” out any spatial differential in the radiance getting to the detector area. For collimated or narrow beam sources, option one is the most commonly chosen solution:

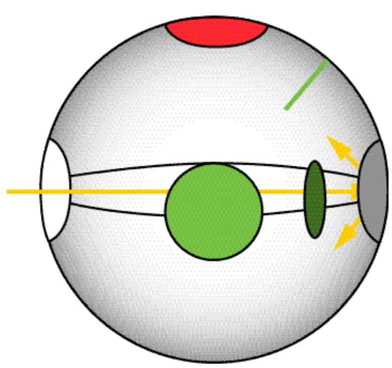


FIGURE 17:
Collimated or Narrow Beam Sphere Set-up Measurement (angles <+/-15° full angle)

4.4.2. Divergent Sources: Diodes, Fibers and Other

Divergent lasers (> +/-15° full angle beam divergence) require a slightly different arrangement of sphere to prevent virtual source and virtual detector overlap. Again, proper baffling prevents light from directly reaching the active area of the detector – in this case we are concerned about source energy directly reaching the detector active area. Also for highly divergent sources one typically uses Option (2) and places a cosine-receptor (diffuser) in front of the detector active area. With a diverging source there is not much "clear" sphere wall area to view integrated radiance. A diffuser helps average out the whole sphere's spatial field – in essence it is an additional layer of "integration" before energy can reach the detector:

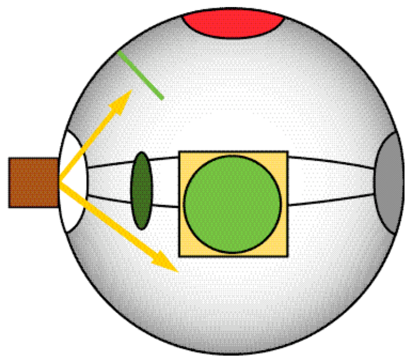


FIGURE 18:
Divergent Power Sphere Set-Up
(Angles >+/-15° full angle)

It is also true that the set-up in Figure 18 works for collimated sources – so, in general, this is the most commonly used arrangement for input source measurements.

4.5 Reflectorized Lamp/LED/Fiber Output Flux Measurement

In general, the rules and diagrams outlined above for laser power measurements also apply to any other type of directional optical source. We are most concerned with the divergence range of the input light source and relative field-of-view of the detector. For light sources with divergence > +/-15° full we show a set-up as pictured in Figure 18. For light sources with divergence > +/-15° full we show a set-up as pictured in Figure 17.

4.6 Internal Lamp Measurements:

There are very specific measurement requirements for lamp flux measurements made with an interior access sphere (light bulb is inserted into sphere's center). SphereOptics produces a line of spheres specifically design to meet the CIE Publication 84 requirements for lamp measurements. Contact your SphereOptics' applications engineer for more information about lamp measurement products.

4.7 LED Measurements:

There are very specific measurement requirements for LED flux measurements with spheres. SphereOptics produces a line of spheres specifically design to meet the CIE Publication 127 requirements for LED measurements. Contact your SphereOptics' applications engineer for more information on our LED measurement product line.

4.8 Luminance and Radiance Uniform Sources:

The use of a sphere for its lambertian - spatially and angularly uniform - light output properties is a very useful and easy set-up to accomplish with a general-purpose sphere. A light source placed in a sphere with some care for the baffle arrangement and some consideration in the field-of-view of the detector or sensor viewing the “features” in the sphere will create a very effective uniform source. There are two scenarios for these types of sources: a source created for an imaging optic (camera or sensor with a lens) – a radiance source, or a source created for a bare sensor and irradiance source.

4.8.1 Radiance/Luminance Sources:

This system can be though of in similar ways as the laser measurement system, but with the light source(s) and detectors in a reciprocal arrangement. We want to make sure the sensor at the exit port of the sphere cannot “see” light sources or physical features like baffles or seams. Our light sources should also provide a good illumination profile of the sphere after one or two bounces of the input light – i.e. the light introduced to the sphere should be isotropic or lambertian if possible. Symmetric light source placement(s) also helps to create good uniformity within a sphere.

A couple of common examples will illustrate light source considerations. A tungsten bulb has a very good isotropic output and therefore can be simply inserted into the sphere. The bulb’s even illumination profile almost completely illuminates the sphere surface evenly at the first strike – subsequent illuminations are even more integrated. However, we do no want the bulb to throw directly light rays at the exit port, so we may add baffles between the source and the exit port of the sphere. Additionally, if we have collimated sources –like a light beam from an external source, we can use the wall of the sphere itself to create a lambertian source via the first reflection of the incoming energy. We would also wish to baffle the first strike area lambertian source of this arrangement from the exit port of the sphere. Additionally, with an external source input, we could interfere with this incoming light beam using a variable aperture (physical iris or blade) and create a variable input to the sphere. The external source and aperture creates a variable level output source.

The field-of-view of the sensor/lens or camera used at the exit port should also not overlap with the sources (or virtual sources), seams of the sphere ports or baffles in the sphere. Physical features in the sphere will represent “viewable” non-uniformities in the sphere. Also, in some cases, for high resolution cameras the best uniformity is achieved by not viewing the wall of the sphere directly, but by viewing the radiance at the port of the sphere or de-focusing on the back of the sphere.

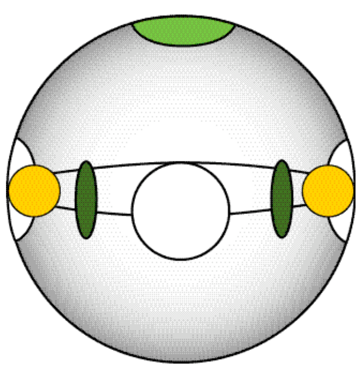


FIGURE 19:
Isotropic Light Sources used to Create a Uniform Source

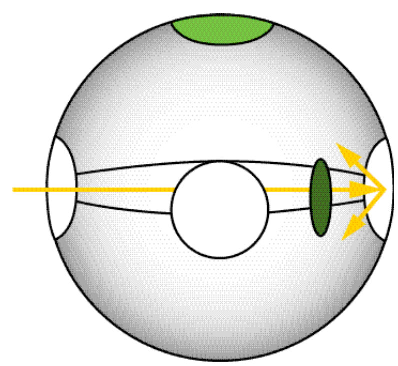


FIGURE 20:
Directional Source used to Create a Uniform Source

Additionally, note that there is a detector on each of these spheres. These detectors provide a relative or absolute monitor of the sphere output level. Light sources and the sphere can change over time and a monitor detector will provide some indication of change. If a calibration is applied to the uniform source output level, then the monitor detector can very often be traceably tied to the output of the source. Such a monitor could also be used to provide a feedback control system to stabilize or control the output of the sphere through a variable aperture/light source assembly.

4.8.2 Irradiance/Illuminance Sources

If the sensor under test has no optics or a hemispherical (~180°) field-of-view then the sphere considerations are slightly different to create a uniform source. Technically, the sensor in this configuration is not looking at anything in the sphere – it is responding to the energy falling on the surface of the detector. In this case, the source design should prevent directional rays from getting to the exit port of the sphere (where the sample is located.) Seams, baffles and other physical features in the sphere are less of a consideration in this test scheme since no imaging is occurring.

An important consideration in using this sphere is that maximum uniformity for the sensor is achieved at the exact plan of the exit port. If the sensor cannot be brought completely to the plane of the exit port then there will be non-uniformities introduced by the physical geometry between the sensor and exit port. For example, consider a CCD sensor chip at the exact exit port plane of a 100% uniform sphere. All pixels whether at the edge of the CCD or at its center can "see" or be illuminated by roughly 180° of incident light when at this exit plane. When this same CCD is spaced back from the exit port by a couple of millimeters, the pixels at the center of the CCD still see very close to 180° of incident light, however, pixels at the very edge of the sensor can only see roughly 90° of incident light angle – this results in non-uniform illumination profile of the CCD even though the sphere is still 100% uniform.

If a CCD cannot be placed directly at the exit port of the sphere for packaging or other physical reasons, then it may alternately be placed a significant distance away from the port of the sphere. At this far field position the irradiance profile of the sphere's energy is again relatively uniform as the sphere is starting to act like a point source. However, the trade off for this distance is energy, which will decrease in proportion to $1/r^2$ with the sensor distance "r" from the sphere.

For a more thorough discussion of uniformity and sphere design issues contact a SphereOptics applications engineer.

4.9 Cosine Receptor:

Since a sphere has theoretically uniform response to input energy regardless of angle it can also be used as a cosine collector. That is, the input energy level in the sphere only varies as the cosine of source's solid angle projection to the sphere's input port as illustrated below:

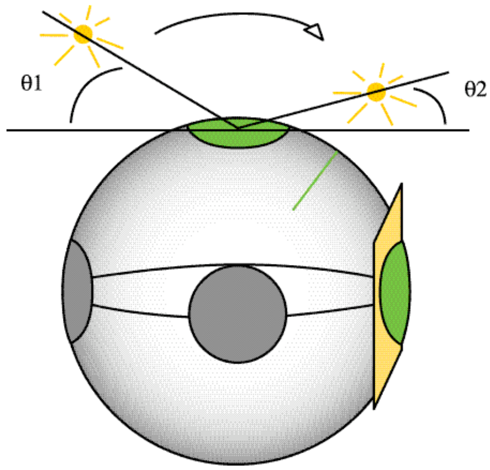


FIGURE 21:
Sphere as a Cosine Receptor:
Detector Response ∝ Cos (θ)

In practice most spheres deviate from perfect cosine response when the light source is at an angle where it presents direct illumination towards the detector location. However, for limited ranges, the sphere can closely emulate a true cosine receptor.

PHOTOMETRIC AND RADIOMETRIC QUANTITIES AND UNITS

Photometric	Quantity	Symbol	SI Unit	Abbreviation
	Luminous flux	Φv	Lumen	lm
	Luminous energy	Q_v	Lumen•second = Talbot	lm•s = Talbot
	Luminous density	U_v	Lumen•second/m^3	lm•s/m^3
	Luminous efficacy	K	lumen/watt	lm W^{-1}
	Luminous exitance	M_v	lumen/m^2	lm/m^{-2}
	Luminous intensity	I_v	candela	cd
	Luminance	L_v	candela/m^2	cd/m^2
	Illuminance	E_v	lumen/m^2 = lux	lm/m2 = lx

Radiometric	Quantity	Symbol	Units	Abbreviation
	Radiant flux (power)	Φ	watts	W
	Radiant energy	Q	joule = watt-second	J = W•s
	Radiant energy density	U	joule/m^3	J/m^3
	Radiant exitance	M	watts/m^2	W/m^2
	Radiant intensity	I	watts/steradian	W/sr
	Radiance	L	watt/steradian/m^2	W/sr/m^2
	Irradiance	E	watts/m^2	W/m^2

Worldwide Representatives

Direct Sales Offices

USA HEADQUARTERS
SphereOptics LLC
Tel: 603-715-3000
Fax: 603-225-3089
Email: sales@sphereoptics.com

USA WEST COAST
SphereOptics LLC
Tel: 858-695-2895
Fax: 858-695-2096
Email: sales@sphereoptics.com

FRANCE
SphereOptics SARL
Tel: +33 (1) 69 07 21 84
Fax: +33 (1) 69 07 71 38
Email: infofr@sphereoptics.com

GERMANY
SphereOptics GmbH
Tel: +49 (0) 7556 929 9666
Fax: +49 (0) 7556 50108
Email: infode@sphereoptics.com

Worldwide Agent Representatives

ARGENTINE / BRAZIL / CHILE
Valley Research Corporation
Tel: 512-453-0310
Fax: 512-453-0547
Email: lab@valleyresearch.com

AUSTRALIA
Lastek Pty Ltd
Tel: +61 8 8443 8668
Fax: +61 8 8443 8427
Email: sales@lastek.com.au

BELGIUM
Tel +32 (0) 14 570 670
Fax: +32 (0) 14 570 679
Email: sales.be@bfioptilas.com

CHINA
Pinnacle International Limited
Tel: +86 571 852 25151
Fax: +86 571 852 25252
Email: sales@pinnacleintl.com

INDIA
Photonics MC
Tel: +91 22 25934171
Fax: +91 22 25903301
Email: photonicsmc@mtnl.net.in

ISRAEL
Rosh Electroptics Ltd.
Tel: +972 9 8627401
Fax: +972 9 8616185
Email: info@roshelop.co.il

ITALY
L.O.T. Italia
Tel: +02-26822104
Fax: +02-26825007
Email: info@lot-oriel.it

JAPAN
Ocean Photonics
Tel: +81 3 5337 0280
Fax: +81 3 5337 0285
Email: sales@oceanphotonics.com

KOREA
KOS, Inc.
Tel: +822-486-7930
Fax: +822-486-7931
Email: kos@kosinc.co.kr

MALAYSIA
Optocom Equiptech Sdn Bhd
Tel: +603-8706 6806
Fax: +603-8706 6809
Email: optocom@tm.net.my

MEXICO / SOUTH AMERICA
Valley Research Corporation
Tel: 512 453 0310
Fax: 512 453 0547
Email: lab@valleyresearch.com

NETHERLANDS
BFi Optilas B.V.
Tel: +31 (0) 172 44 60 60
Fax: +31 (0) 172 44 34 14
Email: sales.nl@bfioptilas.com

SINGAPORE
Acexon Technologies Pte. Ltd.
Tel: +65 6565 7300
Fax: +65 6565 7005
Email: sales@acexon.com

SPAIN
Iberlaser, s.a.
Tel: +34 91 658 67 60
Fax: +34 91 654 17 00
Email: info@iberlaser.com

SWEDEN
TestElek Svenska AB
Tel: +46 8 17 96 00
Fax: +46 8 17 78 70
Email: info@testelek.se

SWITZERLAND
L.O.T.-Oriel Suisse SARL
Tel: +41 0 21 869 9033
Fax: +41 0 21 869 9308
Email: suisse@lot-oriel.com

TAIWAN - HSINSHIN
Isuzu Optics Corp.
Tel: +886-3-5526689
Fax: +886-3-5526796
Email: hao@isuzuoptics.com.tw

TAIWAN - TAIPEI
Toptical Scientific Corp.
Tel: +886-2-2346-1510
Fax: +886-2-2346-1520
Email: toptical@ms17.hinet.net

UNITED KINGDOM
Precision Photometrics
Tel: +44 44 131 29 4843
Email: info@precisionphotometrics.com

SphereOptics

www.sphereoptics.com