Integrating Sphere Uniform Light Source Applications

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Leadership in Reflectance Technology

TECH GUIDE

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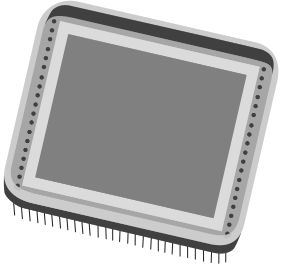
INTRODUCTION

Uniform source systems provide uniform radiance or irradiance. Their applications include focal-plane array or complete camera testing, pixel gain normalization, photographic sensitometry, and remote-observation system calibration. Sources are used in the ultraviolet, visible, and infrared regions of the spectrum. Most uniform sources use integrating spheres, while some use lasers, lamps, and other sources alone. Sphere systems are highly lambertian and show very uniform radiance distribution. This *Techguide* examines some of these applications, discusses how Labsphere calibrates uniform sources, and provides examples of custom uniform light systems we have designed.

Labsphere's design engineers are ready to help you with your uniform source needs. After you have had a chance to read this booklet, call us at (603) 927-4266 and one of our technical representatives will assist you with your application.

1.0 TYPICAL APPLICATIONS

1.1 Focal-Plane Arrays



Focal-plane arrays (FPA) are multi-element photosensitive detectors used in electronic imaging. Their applications range from inexpensive video and still cameras in the consumer market to advanced scientific imagers for space-borne remote sensing. 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). They can be linear or two-dimensional and their size is usually not more than several centimeters.

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. Photoresponse Nonuniformity (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. This type of application is an *irradiance* application.

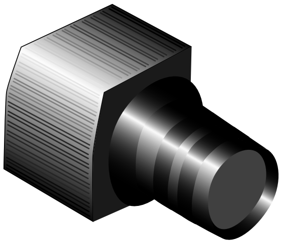
Offset normalization is simply performed by providing zero irradiance on the array and setting the output signal of each pixel to zero. During gain normalization, a uniform source produces irradiance on the array that is equal at each pixel. The gain, or responsivity, of each pixel is set so that each 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 may be produced by placing the FPA at the exit port of a uniform source sphere. At the exit port, the array will be 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. (See Appendix A — page 10.)

It is useful to know the responsivity of an array. A uniform source can provide a known amount of illumination. When the illumination level is varied and the array's response measured, the responsivity, linearity, and dynamic range can be characterized. By introducing narrowband light of various wavelengths, the spectral response can also be measured.

A uniform source system is an excellent tool to measure an array's photon transfer curve. By varying the level of input illumination, one can measure the noise in the array and determine the sources of that noise: noise "floor" under low photon flux conditions; shot noise as illuminance increases: and FPN at higher illuminance. This technique also gives the dynamic range of the array, including its associated readout electronics.[1]

1.2 Imagers



Digital cameras, remote-sensing systems, and other electronic imagers must be normalized in much the same way as bare FPAs. 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 irradiance that varies with field angle. The most common variation is the cosine-fourth law.[2] *(see Figure 1)* A procedure similar to that described for simple FPAs will correct for cosine-fourth irradiance falloff and other sources of irradiance variation in the image. This application is a *radiance* application.

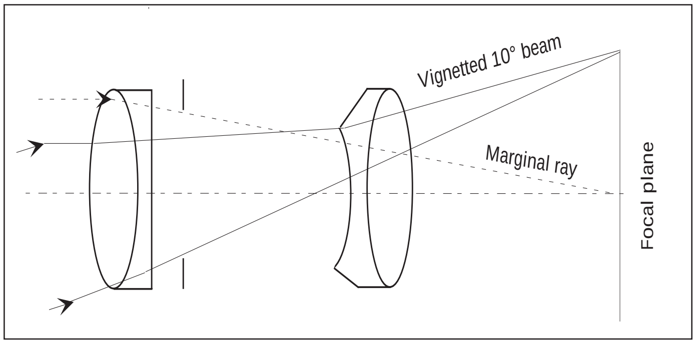


FIGURE 1

1.3 Sensitometry

Manufacturers of silver-halide photographic materials must perform quality-control tests on their products. The light source irradiating the target must be uniform over a large area. The irradiation must be controllable in level and, in some cases, spectral content. Complete systems must also incorporate a manufacturer's process-control data collection requirements, such as logging data and providing statistical information. This application is an *irradiance* application.

In some cases, a uniform source sphere is the best choice for sensitometry. It can provide optical power efficiency and excellent uniformity. A sphere also allows the designer to mix several sources to provide simultaneously a multi-source spectrum and uniform irradiance. In other applications, a non-sphere based system is best. The difference is in the geometry. If diffuse illumination is required, then we place the sample at the sphere's exit port. When directional illumination is required, a beam is projected at the target.

2.0 SYSTEM DESIGN CONSIDERATIONS

There are several system design requirements below that are common to most uniform source applications. These are the parameters that the designer must take into account when formulating the source's specifications.

2.1 Sphere Size

The size of the source is often specified explicitly in imaging applications. The diameter of the exit port of a sphere, for example, may be based on the object size, aperture, and field of view of the camera under test. In irradiation applications, the size of the source may be designed based on parameters such as the irradiated area and distance from the source to the target. The size of the integrating sphere is then based on the required size of the exit port. The larger the sphere with respect to the exit port, the greater the uniformity, all other things being equal. However, the power required in the sphere to produce a particular radiance or irradiance increases with sphere size. Sometimes, designers must make compromises on the overall size of the system based on available volume for the system, shipping and storage constraints, and cost.

2.2 Uniformity

A uniform source system will provide radiance and irradiance uniformity. As important as the uniformity value, is the method by which uniformity is measured. Common methods include mapping the radiance of the source using an imaging system, or mapping the irradiance at a target plane using a simple detector with a wide field of view. Irradiance uniformity when measured a distance from the source, depends on geometrical theory as well as the radiance uniformity of the source (see Appendix). In some applications, especially remote sensing, angular uniformity mapping is also required.

2.3 Spectrum

The spectral distribution of the light coming from a sphere is based on the light source and the reflectance of the sphere material. Spectral requirements influence the choice of light sources and reflectance materials. Most uniform source systems incorporate tungsten-halogen lamps. By placing the lamps outside of the sphere, filters allow the spectrum to be tailored to the desired shape.

Spheres allow one important feature that is not available using other methods: multiple sources can be mixed in the sphere to produce uniform output. For example, several narrowband sources, such as lasers, LEDs, or red, green, and blue sources, can be input to the sphere. Light from the various sources will be integrated and the resulting output will be the combination of the relative distributions, as well as the effects of the sphere wall reflectance.

2.4 Light Level

The quantity of radiance depends on the size of the sphere, the reflectance of the sphere wall, and the amount of source power input to the sphere. Irradiance at a distance from the exit port depends on the radiance of the exit port, its size, the distance from the sphere to the target, and the size of the target (see Appendix).

It is also important to consider varying the light output level. The radiance of a sphere with multiple sources, for example, will vary with the number and power of the sources that are activated. Resolution in the adjustment is sometimes critical. The user may require setting radiance levels very precisely, rather than just depending on turning lamps on and off to achieve a coarse adjustment. Variable attenuators are often used for this purpose.

2.5 Mechanical Configuration

There are a great variety of mechanical configurations possible in a design. The camera or irradiated target, for example, can face in a vertical or horizontal direction. Space constraints in the area where the sphere is to be used may also dictate some aspects of its design.

The location of the sources within the sphere depends on how the sphere is used. When used as a source of radiance, for example, the designer must take into account the object size, aperture, and field of view of the camera that will image the sphere's exit port. Baffles, made from a reflectance material similar to that of the sphere wall, are often used to improve uniformity by preventing the optical system under test from directly viewing a source of radiation within the sphere.

2.6 Monitoring

It is customary to use a detector to monitor the output of a sphere. The detector might be a simple unfiltered sensor, a photopic detector designed to mimic the sensitivity of the human eye, or some type of spectral detector that will provide the spectral radiance or irradiance of the system. Systems can simply read the output of the detector or, in more advanced sources that combine adjustability with software, allow the operator to set a specific output level and automatically adjust the system to that level.

3.0 FREQUENTLY-ASKED QUESTIONS

Which sphere coating or material should I choose?
The material depends not only on the spectral requirements, but on the operating environment. For example, some diffuse coatings are more robust than others when used in humid environments. Damage thresholds in high energy applications must also be considered.

Coatings and materials used in integrating spheres have reflectances between 95% and 99%. When a perfect diffuse reflector is illuminated with uniform irradiance it behaves as a perfect diffuse source — a Lambertian source. Labsphere's Spectralon®, Spectraflect®, Duraflect™ and Infragold™ coatings provide excellent Lambertian properties.

What size sphere do I need?
A good design guideline is that the sphere diameter should be at least three times the diameter of the exit port. Any smaller, and uniformity will be compromised. Much larger, and many more lamps will be required with very little payoff in uniformity. To achieve a certain output level, the input power varies as the square of the sphere diameter, when all other parameters are held constant.

How can I monitor the sphere output?
In visual applications, a photopic detector is sufficient. The reading from a "broadband" measurement, such as an unfiltered detector, depends on the spectrum of the source. Since the spectrum is stable, a simple detector provides adequate monitoring. Of course, a detector whose responsivity is stable over time is required for accurate calibration. In some cases, the detector must be thermally controlled so that its responsivity does not change.

How can I control the output level?
The simplest way is to use a system that has multiple lamps, sometimes of various powers. Lamps are activated to produce the desired output level. Where more resolution is required, an external lamp with a variable component is used. Variability of the light is achieved using filters or a variable shutter. Controlling output level by adjusting the current to the lamps is not recommended, since large spectral shifts will occur.

4.0 SYSTEM CALIBRATION

A uniform source system is only as good as its calibration. For example, when a specific radiance is required, it is necessary to know that radiance to a reasonable certainty.

Under most uses, such as laboratory environments, a sphere's calibration is certified for 50 hours of lamp life. Using a power supply that slowly ramps lamp current to its operating value, careful physical handling of the lamp, and maintaining a clean sphere will preserve accurate calibration. It is often useful to have a secondary standard from which to transfer the calibration to the system in use. The standard might be a small uniform source sphere. While the main system would be used often, and possibly for several hours per use, the calibration sphere's lamp will be used only for calibrating the main system thereby preserving its calibration.

4.1 Luminance

The most common uniform source calibration performed is luminance. A luminance meter is calibrated by the manufacturer and traceable to a national laboratory. The meter measures the sphere luminance by viewing the exit port and providing the luminance in the display. In uniform sources that include a system control radiometer and photopic detector, the detector photocurrent is measured. The system control is programmed with the responsivity. Thus, the uniform source system will display the luminance of the sphere. Typical units are foot-lamberts and cd/m^2. All Labsphere calibration and measurement certificates include traceability authority and a report on measurement uncertainty.

4.2 Spectral Radiance

Spectral radiance is measured in much the same way. In place of the luminance meter, a spectroradiometer images the sphere exit port via a series of mirrors, a chopper, a monochromator, and a detector as shown in *Figure 2*. The monochromator's gratings and detectors are changed as appropriate for the spectral range measured. The spectroradiometer can measure spectral radiance from 300nm to 2400nm, covering the near ultraviolet, visible, and near infrared regions. Typical units are W/m^2•steradian•µm. When necessary, spectral radiance responsivity can be programmed into the control system. This capability varies with the type of monitor detector used.

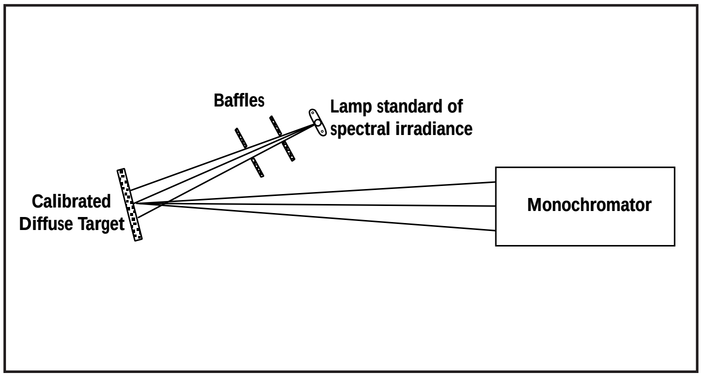


FIGURE 2

Some applications require radiance integration in a waveband, rather than individual spectral radiance values at a number of wavelengths. This measurement is achieved by first measuring the spectral radiance then using numerical techniques to integrate over the waveband of interest. Spectral weighting can also be performed to account for the sensitivity of a customer's detector or transmittance through an optical system.

The spectroradiometer is calibrated using a lamp and a Spectralon target. The lamp is a source of known spectral irradiance that is traceable to a national laboratory. The target's reflectance is measured in Labsphere's Reflectance Spectroscopy Laboratory and is also traceable to a national authority. Thus, when light from the lamp is directed onto and reflects from the target, we have a known source of spectral radiance. The spectroradiometer images this target, provides an output signal, and the spectroradiometer's responsivity is calibrated. The target is replaced immediately with the exit port of the sphere, and the uniform source is measured. The spectroradiometer is calibrated each day to ensure reliable measurements.

4.3 Irradiance

Irradiance and illuminance are most often calibrated using a detector (spectral or photopic) and an optical system. The most reliable optical system is a small integrating sphere, which provides a complete hemispherical field of view for the measurement (*see Figure 3*). In some cases, the application requires limiting the field of view with baffles or other optics. The irradiance meter is calibrated in much the same way as the spectroradiometer but specifically to the individual application. Typical units are foot candles, lux, and W/m^2.

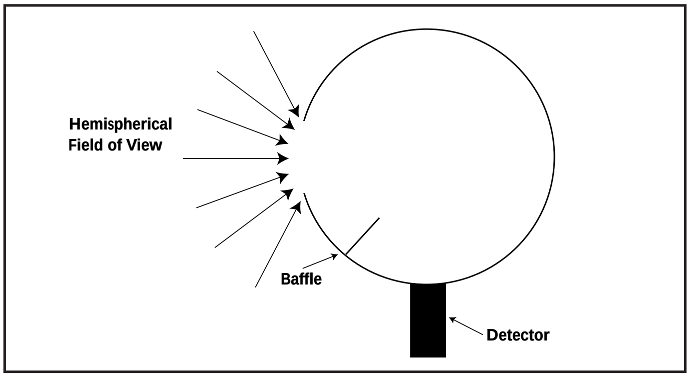


FIGURE 3

4.4 Uniformity

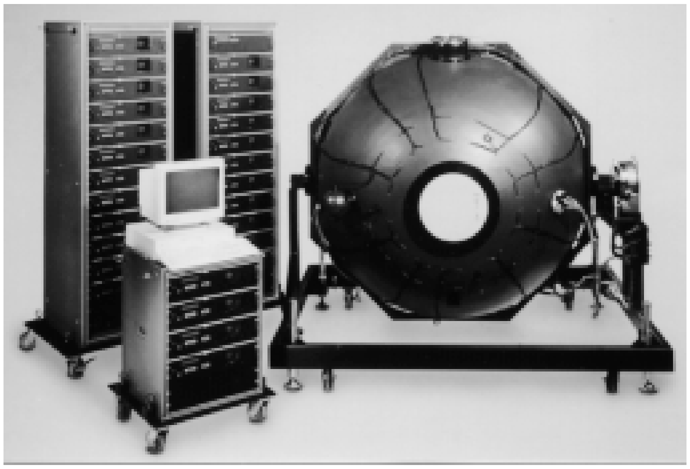
The most common uniformity measurement is photopic mapping. A luminance meter images a small portion of the exit port and is then translated across the exit port measuring some number of points. The optical axis of the luminance meter remains perpendicular to the plane of the exit port. Each reading is normalized to that of the center of the exit port, and a relative luminace mapping is reported. Depending on the application, the imaged spot size, numerical aperture of the meter, and number of points measured can be varied. Varying the angle of the meter's optical axis allows us to perform an angular mapping at any point on the exit port. This technique is especially appropriate for infinite-conjugate systems.

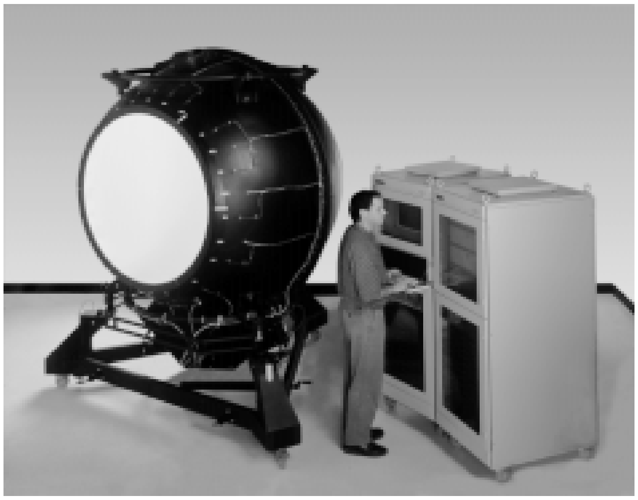
Irradiance uniformity is accomplished using a small integrating sphere and a detector in much the same way as the photopic mapping. The detector-sphere input port is placed at the exit port of the uniform source and translated across the exit port plane.

LABSPHERE CUSTOM DESIGNED UNIFORM SOURCE SYSTEMS

1.6 meter Uniform Source

Labsphere designed, built, and calibrated a 1.6 meter uniform source system for a spaceborne-camera calibration. The sphere featured 450mm rear port for veiling glare evaluation, and height and elevation angle adjustment. The sphere's main components were twenty-eight (28) lamps of various power levels, including one external to the sphere, a variable attenuator for the external lamp, and five thermoelectrically cooled detectors. Each detector was fitted with a narrowband filter. Labsphere included software that turned lamps on and off, set the variable attenuator for the external lamp, read the detectors, and calculated spectral radiance over a wide wavelength range using numerical techniques.



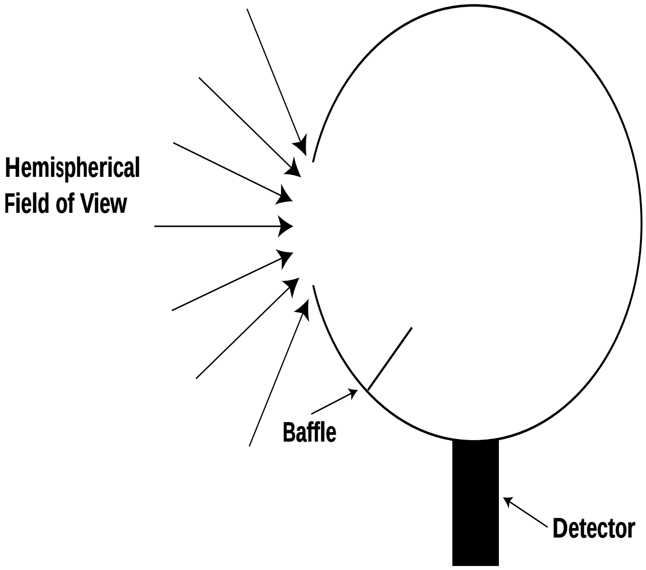


2m High-Power Uniform Calibration Source

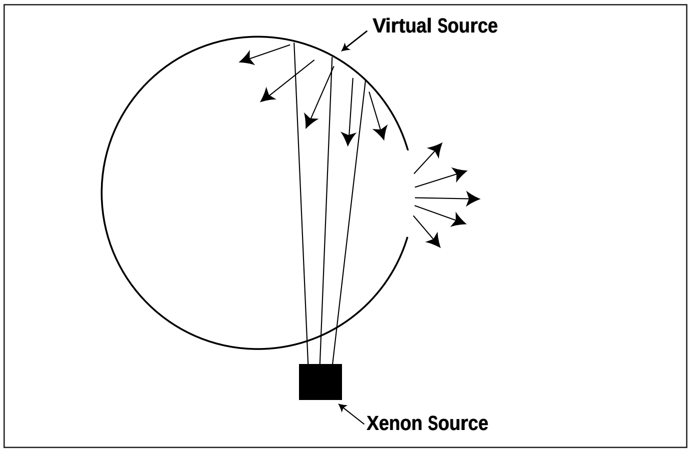
Labsphere designed and manufactured a 2 meter diameter uniform source sphere system for an international aerospace concern. This system is to be used to calibrate spaceborne cameras for several missions. Requirements included spectral radiance, optical stability, Class 100 cleanroom compatability, remote location of the control electronics, triple redundancy for electrical safety, and precise mechanical positioning. Although the sphere had an unusually large exit port (1.2m dia.) it produced radiance with uniformity in excess of 95%.

Sensitometer Uniform Source

A manufacturer of silver-halide photographic products asked Labsphere to develop a sensitometer for quality assurance. The manufacturer required a system that allowed them to vary and measure the source illuminance and color temperature. It was also necessary that the sensitometer be easy-to-use, as it would be operated in a dark environment. Windows™ software enabled the customer to have a simple user interface and to collect data to ensure consistent product quality. Software also needed to allow for maintaining a large database of test results. This system is one of the few Labsphere uniform sources that does not use an integrating sphere. We simply used a 300W lamp whose distance from the target could be adjusted from 400mm to 600mm.

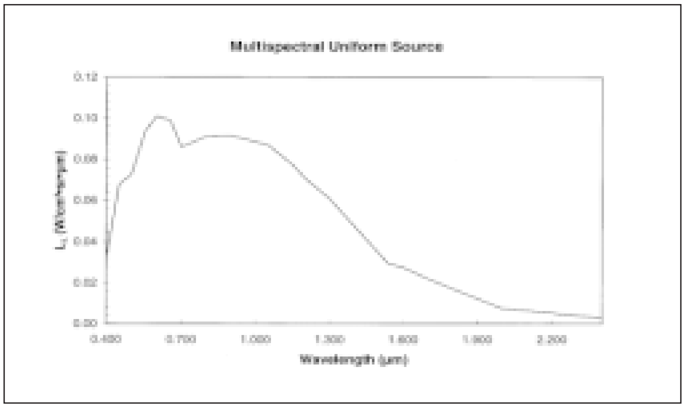


Multispectral Uniform Source

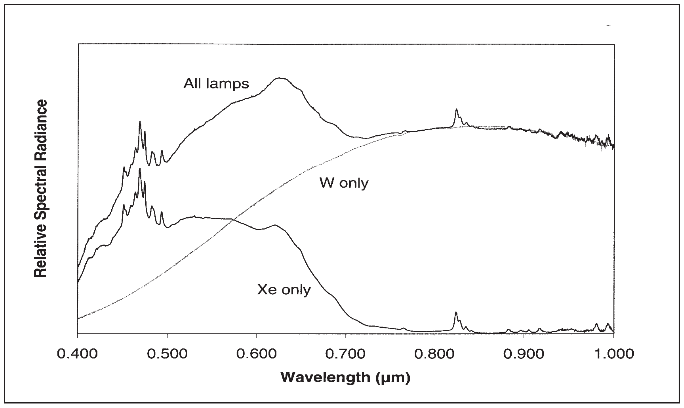


For an aerospace application, Labsphere made a 76cm uniform source sphere that included two types of lamps: tungsten halogen and xenon arc. Because the spaceborne camera was viewing terrestrial energy, the application required high spectral radiance in the blue region of the spectrum and less, but a significant amount, in the near infrared region. The solution was to use the two lamp types to combine their spectra within the sphere.

One concern when using xenon arc lamps is their stability. The arc wanders and changes in size over time. Fortunately, an integrating sphere is somewhat less sensitive than, say, an optical system that images the arc itself. The lamp consists of an integral reflector with the arc at its focus. When the arc wanders, the beam shifts its direction. Small amounts of shift, even a few degrees, will simply cause the to beam move within the sphere. A sphere’s unique integration properties make it quite insensitive to such variation. The sphere radiance exhibited short-term stability of about 0.25% with one xenon lamp operating. [3]



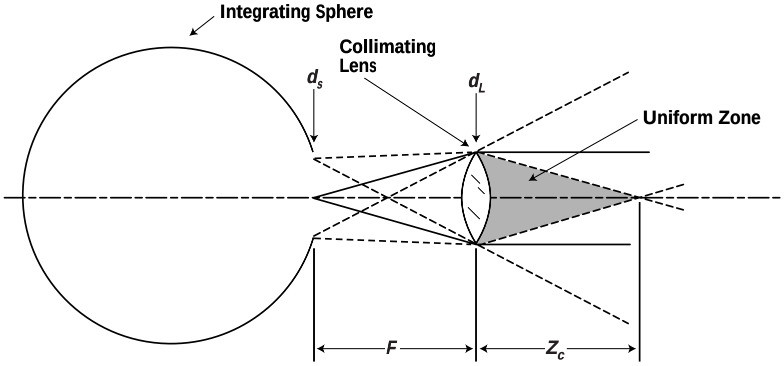
System output with all lamps on, measured with a 10 nm bandwidth



Relative Spectra — 2 nm bandwidth, data every 0.5 nm

Projected Uniform Source

Under certain conditions, it is desirable to project a uniform beam of light onto a target. This technique is especially useful when one does not have access to the target. For example, the target might be in a vacuum or other type of environmental chamber. In addition, a "searchlight" projector provides a uniform volume in which the irradiance remains constant, allowing non-critical alignment of the sample.[4] With the sphere's exit port at the focus of a collimating lens, the uniform zone forms a conical shape in image space with the base of the cone at the lens. The length of the zone, Z_c, is determined by the diameter of the exit port, d_s, the focal length, F, and diameter of the lens, d_L. [5]



APPENDIX A

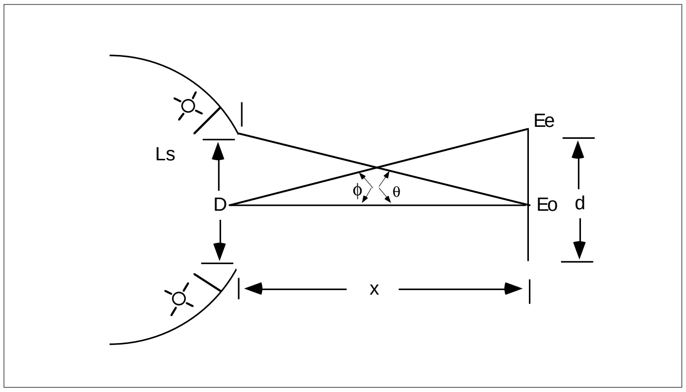
Irradiance Uniformity

Radiance is the flux density leaving a radiant surface as viewed from a distance away from the surface. A *Lambertian* surface features a radiance that is perfectly diffuse, independent of viewing angle. *Irradiance* is the flux density falling on a surface and is measured at the plane of the surface. Integrating sphere sources are most often used to test an imaging system. The desired effect is uniform radiance within the field-of-view of the system under test.

The source can be used to back illuminate a printed or etched image such as photographic film for image digitization or resolution targets for MTF testing.

It is sometimes desired to use the sphere source for testing a non-imaging device such as a CCD or similar array detector. In this case the desired effect is uniform irradiance. The device under test is often placed coaxial with, but at some distance away from the port of the integrating sphere source. When used in this way, the two important quantities to be determined are the axial irradiance as well as the irradiance at the off-axis edge.

FIGURE 1A



In Figure 1A, the axial irradiance, E_0 is given by:

$$E_0 = \pi L_s \sin^2\theta$$ **EQ. 1**

Even for a perfectly Lambertian, perfectly uniform circular source, the uniformity of the irradiance across a plane object at a finite distance will vary with the off-axis angle ϕ. The uniformity fall off is given in Table 1 where both the distance and the dimension of the object are expressed as multiples of the sphere port diameter, x/D and d/D respectively. Uniformity is defined as the ratio of the irradiance at the edge of the object to the axial irradiance, E_e/E_o.

Examination of Table 1 reveals that the uniformity is 100% at the plane of the port. It decreases as the object is moved away from the port for a short distance and improves as the distance becomes sufficiently long. This phenomenon can be illustrated graphically as shown in Figure 2A.

For small values of both θ and ϕ (<10°), the irradiance at the edge is given by the commonly used *cos⁴ϕ law of illumination* where:

$$E_e = E_0 \cos^4\phi$$ **EQ. 2**

In the examples illustrated for a source diameter equal to or larger than the object, the $\cos^4\phi$ law predicts the edge irradiance to within 1% for source to object distances at least two times larger than the source diameter. At this distance, the uniformity is within 10%, however, the irradiance is less than ≈6% of the value at the plane of the port.

It is important to note that Table 1 and Figure 2 display calculated theoretical values of uniformity for the ideal perfectly Lambertian source. Laboratory measurements of real integrating sphere sources correlate extremely well with these predicted values. Therefore, the data provided can be used as design guidelines in choosing the correct uniform source for a particular application.

FIGURE 2A

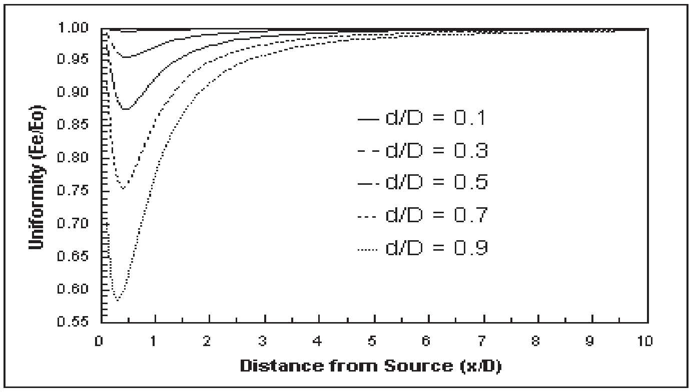


TABLE 1

	Irradiance Uniformity (Ee/Eo) Distance from Source (x/D)											
Object Diameter d/D	**0.00**	**0.10**	**0.20**	**0.25**	**0.50**	**0.75**	**1.00**	**1.50**	**2.00**	**2.50**	**3.00**	**5.00**	**10.00**
0.1	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
0.2	1.00	1.00	0.99	0.99	0.98	0.98	0.99	0.99	1.00	1.00	1.00	1.00	1.00
0.3	1.00	0.99	0.98	0.97	0.96	0.96	0.97	0.98	0.99	0.99	1.00	1.00	1.00
0.4	1.00	0.99	0.96	0.94	0.92	0.93	0.95	0.97	0.98	0.99	0.99	1.00	1.00
0.5	1.00	0.97	0.92	0.90	0.88	0.90	0.92	0.96	0.97	0.98	0.99	1.00	1.00
0.6	1.00	0.95	0.88	0.85	0.82	0.86	0.89	0.94	0.96	0.97	0.98	0.99	1.00
0.7	1.00	0.92	0.81	0.78	0.76	0.81	0.86	0.92	0.95	0.96	0.97	0.99	1.00
0.8	1.00	0.84	0.72	0.69	0.70	0.76	0.82	0.89	0.93	0.95	0.97	0.99	1.00
0.9	1.00	0.70	0.60	0.59	0.62	0.71	0.78	0.87	0.92	0.94	0.96	0.98	1.00
$\sin^2\theta$	1.000	0.962	0.862	0.800	0.500	0.308	0.200	0.100	0.059	0.038	0.027	0.010	0.002
$\pi \sin^2\theta$	3.142	3.021	3.708	2.513	1.571	0.967	0.628	0.314	0.185	0.121	0.085	0.031	0.008

Note: Boundary lines delineate regions of 98%, 95%, and 90% irradiance uniformity

REFERENCES

1. G.C. Holst, *CCD Arrays, Cameras, and Display*s, 2 ed. (JCD Publishing, Winter Park, Florida, 1998), pp. 133-44.

2. W.J. Smith, *Modern Optical Engineering*, 2 ed. (McGraw Hill, New York, 1990), p. 145.

3. D.P. D'Amato, "Spectral radiance and temporal stability of a uniform radiance source integrating sphere with enhanced blue performance," Proc. Soc. Photo-Opt. Instrumentation Engineers, 3428,2 (1998).

4. J.D. Scheuch, "Modeling of constant irradiance illumination system," Proc. Society Photo-Opt. Instrument Engineers, 3428, (1998)

5. R.W. Boyd, *Radiometry and the Detection of Optical Radiation* (Wiley, New York, 1983), pp. 86-89.