Designation: E2387 – 05 (Reapproved 2011)

Standard Practice for Goniometric Optical Scatter Measurements[1]

This standard is issued under the fixed designation E2387; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This practice describes procedures for determining the amount and angular distribution of optical scatter from a surface. In particular it focuses on measurement of the bidirectional scattering distribution function (BSDF). BSDF is a convenient and well accepted means of expressing optical scatter levels for many purposes. It is often referred to as the bidirectional reflectance distribution function (BRDF) when considering reflective scatter or the bidirectional transmittance distribution function (BTDF) when considering transmissive scatter.

1.2 The BSDF is a fundamental description of the appearance of a sample, and many other appearance attributes (such as gloss, haze, and color) can be represented in terms of integrals of the BSDF over specific geometric and spectral conditions.

1.3 This practice also presents alternative ways of presenting angle-resolved optical scatter results, including directional reflectance factor, directional transmittance factor, and differential scattering function.

1.4 This practice applies to BSDF measurements on opaque, translucent, or transparent samples.

1.5 The wavelengths for which this practice applies include the ultraviolet, visible, and infrared regions. Difficulty in obtaining appropriate sources, detectors, and low scatter optics complicates its practical application at wavelengths less than about 0.2 µm (200 nm). Diffraction effects start to become important for wavelengths greater than 15 µm (15 000 nm), which complicate its practical application at longer wavelengths. Measurements pertaining to visual appearance are restricted to the visible wavelength region.

1.6 This practice does not apply to materials exhibiting significant fluorescence.

1.7 This practice applies to flat or curved samples of arbitrary shape. However, only a flat sample is addressed in the discussion and examples. It is the user's responsibility to define an appropriate sample coordinate system to specify the measurement location on the sample surface and appropriate beam properties for samples that are not flat.

1.8 This practice does not provide a method for ascribing the measured BSDF to any scattering mechanism or source.

1.9 This practice does not provide a method to extrapolate data from one wavelength, scattering geometry, sample location, or polarization to any other wavelength, scattering geometry, sample location, or polarization. The user must make measurements at the wavelengths, scattering geometries, sample locations, and polarizations that are of interest to his or her application.

1.10 Any parameter can be varied in a measurement sequence. Parameters that remain constant during a measurement sequence are reported as either header information in the tabulated data set or in an associated document.

1.11 The apparatus and measurement procedure are generic, so that specific instruments are neither excluded nor implied in the use of this practice.

1.12 For measurements performed for the semiconductor industry, the operator should consult Practice SEMI ME 1392.

1.13 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E284 Terminology of Appearance

E308 Practice for Computing the Colors of Objects by Using the CIE System

E1331 Test Method for Reflectance Factor and Color by Spectrophotometry Using Hemispherical Geometry

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[1] This practice is under the jurisdiction of ASTM Committee E12 on Color and Appearance and is the direct responsibility of Subcommittee E12.03 on Geometry.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

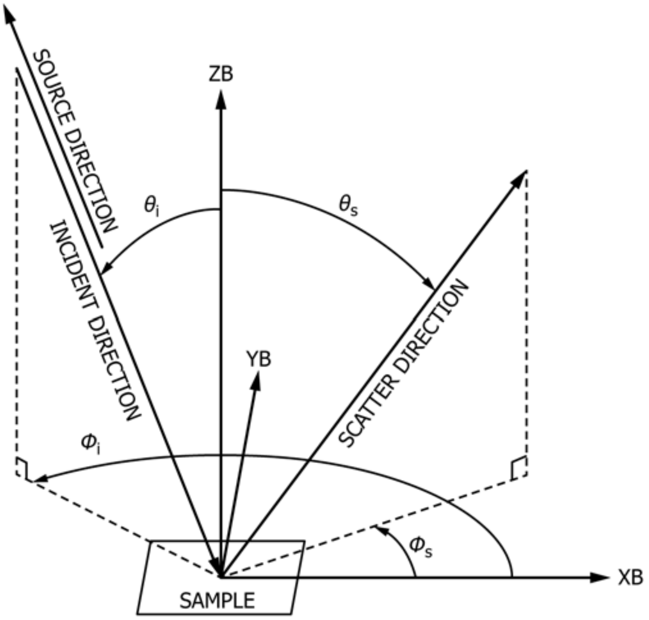

FIG. 1 Angle Conversions

2.2 *ISO Standard:*

ISO 13696 Optics and Optical Instruments—Test Methods for Radiation Scattered by Optical Components[3]

2.3 *Semiconductor Equipment and Materials International (SEMI) Standard:*

ME 1392 Practice for Angle Resolved Optical Scatter Measurements on Specular and Diffuse Surfaces[4]

3. Terminology

3.1 *Definitions:*

3.1.1 Definitions of terms not included here will be found in Terminology E284.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *absolute normalization method, n*—a method of performing a scattering measurement in which the incident power is measured directly with the same receiver system as is used for the scattering measurement.

3.2.2 *angle of incidence,* θi, *n*—polar angle of the source direction, given by the angle between the source direction and the surface normal; see Fig. 1.

3.2.2.1 *Discussion*—See Discussion of *scatter polar angle*.

3.2.3 *aspecular angle,* α, *n*—the angle between the specular direction and the scatter direction, the sign of which is positive for backward scattering and negative for forward scattering.

3.2.3.1 *Discussion*—For scatter directions in the plane of incidence (with $\varphi_s = 0$ and $\varphi i = 180°$), the aspecular angle is given by:

$$\alpha = \theta_i - \theta_s \tag{1}$$

A more general expression for the aspecular angle, valid for all incident and scattering directions, is given by:

$$\alpha = \cos^{-1}[\cos\theta_i\cos\theta_s - \sin\theta_i\sin\theta_s\cos(\varphi_s - \varphi_i)] \tag{2}$$

Since the arccosine of a value is always positive, the sign must be separately chosen so that it is positive when the scattering direction is behind the specular direction and negative when the scattering direction is forward of the specular direction. The convention adopted here is that it is positive if:

$$\sin\theta_s\cos(\varphi_s - \varphi_i) > \sin\theta_i \tag{3}$$

and negative otherwise. Fig. 2 illustrates the regions of positive and negative aspecular angles.

3.2.4 *beam coordinate system, n*—a coordinate system parallel to the sample coordinate system, whose origin is the geometric center of the sampling region, used to define the angle of incidence, the scatter angle, the incident azimuth angle, and the scatter azimuth angle.

3.2.5 *bidirectional reflectance distribution function, BRDF, n*—the sample BSDF measured in a reflective geometry.

3.2.6 *bidirectional scattering distribution function BSDF, n*—the sample radiance L_e divided by the sample irradiance E_e for a uniformly-illuminated and uniform sample:

$$\mathrm{BSDF} = \frac{L_e}{E_e} \quad [\mathrm{sr}^{-1}] \tag{4}$$

3.2.6.1 *Discussion*—BSDF is a differential function dependent on the wavelength, incident direction, scatter direction, and polarization states of the incident and scattered fluxes. The BSDF is equivalent to the fraction of the incident flux scattered per unit projected solid angle:

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[3] Available from International Organization for Standardization (ISO), 1, ch. de la Voie-Creuse, Case postale 56, CH-1211, Geneva 20, Switzerland, http://www.iso.ch.

[4] Available from Semiconductor Equipment and Materials International (SEMI), 3081 Zanker Rd., San Jose, CA 95134, http://www.semi.org.

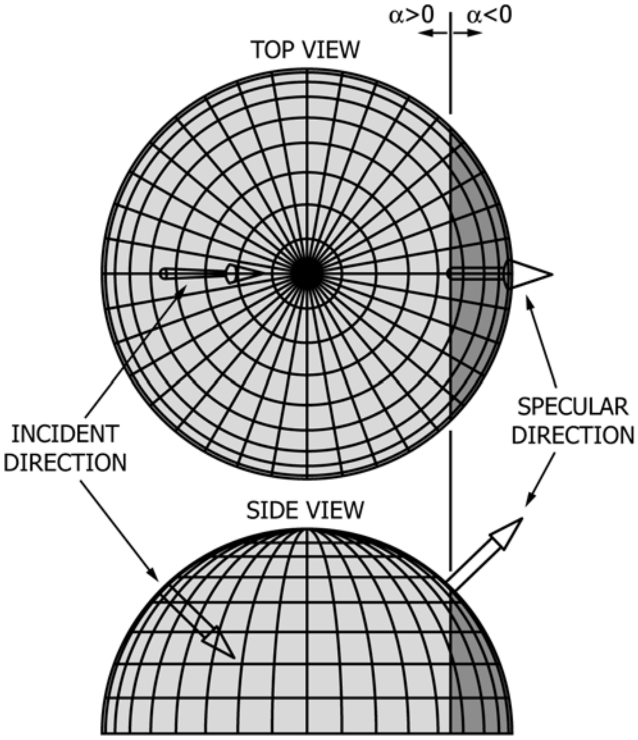


FIG. 2 Definition of the Sign of the Aspecular Angle

$$\mathrm{BSDF} = \lim_{\Omega \to 0} \frac{P_s}{P_i \Omega \cos \theta_s} \quad [\mathrm{sr}^{-1}] \tag{5}$$

The BSDF of a lambertian surface is independent of scatter direction. The BSDF of a specularly reflecting surface has a sharp peak in the specular direction. If a surface scatters non-uniformly from one position to another then a series of measurements over the sample surface must be averaged to obtain suitable statistical uncertainty.

3.2.7 *bidirectional transmittance distribution function, BTDF, n*—the sample BSDF measured in a transmissive geometry.

3.2.8 *BSDF instrument signature, n*—the mean scatter level detected when there is no sample scatter present expressed as BSDF.

3.2.8.1 *Discussion*—The BSDF instrument signature is given by the DSF instrument signature divided by $\cos\theta_s$. The BSDF instrument signature depends upon scattering angle. Because of the factor $\cos\theta_s$, if it is not below the noise equivalent BSDF, it diverges to infinity at $\theta_s = 90°$.

3.2.9 *colorimetric BSDF, n*—the angle-resolved multi-parameter color specification function which is scaled so that the luminance factor *Y* corresponds to the photometric BSDF.

3.2.9.1 *Discussion*—The colorimetric BSDF consists of three color coordinates as a function of the scattering geometry. One of color coordinates corresponds to the luminance factor *Y* and is usually expressed as the ratio of the luminance of a specimen to that of a perfect diffuser. For the colorimetric BSDF, this color coordinate is replaced by the photometric BSDF. The specific illuminant (for example, CIE Standard Illuminant D65), set of color matching functions (for example, CIE 1931 Standard Colorimetric Observer), and the color system (for example, CIELAB) must be specified and included with any data.

3.2.10 *differential scattering function, DSF, n*—the fraction of incident light scattered per unit solid angle, given by:

$$\mathrm{DSF} = \lim_{\Omega \to 0} \frac{P_s}{P_i \Omega} = \mathrm{BSDF}\cos\theta_s \tag{6}$$

3.2.11 *directional transmittance factor, T_d, n*—the ratio of the BTDF to that for a perfectly transmitting diffuser (defined as 1/π), given by:

$$T_d = \pi\ \mathrm{BTDF} \tag{7}$$

3.2.12 *directional reflectance factor, R_d, n*—the ratio of the BRDF to that for a perfect reflecting diffuser (defined as 1/π), given by:

$$R_d = \pi\ \mathrm{BRDF} \tag{8}$$

3.2.13 *DSF instrument signature, n*—the mean scatter level detected when there is no sample scatter present expressed as a DSF.

3.2.13.1 *Discussion*—The DSF instrument signature provides an equivalent DSF for a perfectly reflecting specular surface as measured by the instrument. The instrument signature includes contributions from the size of the incident light beam at the receiver aperture, the diffraction of that beam, and stray scatter from instrument components. For high-sensitivity systems (those whose NEDSF strives for levels below about 10^{-6} sr^{-1}), the limitation on instrument signature is normally Rayleigh scatter from molecules within the volume of the incident light beam that is sampled by the receiver field of view. The instrument signature can be measured by removing the sample and scanning the receiver through the incident beam in a transmission configuration. The signature can also be measured by scanning a reference sample, whose scatter is expected to be significantly lower than that of the specimen being studied, in which case the signature is adjusted by dividing by the reference sample reflectance. It is necessary to furnish the instrument signature when reporting BSDF data so that the user can decide at what scatter direction the measured sample BSDF or DSF is lost in the signature. Preferably the signature is at least a few decades below the sample data and can be ignored. The DSF instrument signature depends upon the receiver solid angle and the receiver field of view.

3.2.14 *incident azimuth angle,* φ_i*, n*—the angle from the *XB* axis to the projection of the source direction onto the *X-Y* plane; when not specified, this angle is assumed to be 180°; see Fig. 1.

3.2.14.1 *Discussion*—See Discussion for *scatter polar angle*.

3.2.15 *incident direction, n*—the central ray of the incident flux specified by θ_i and φ_i in the beam coordinate system, pointing from the illumination to the sample.

3.2.15.1 *Discussion*—The incident direction is the opposite of the source direction.

3.2.16 *incident power,* P_i*, n*—the radiant flux incident on the sample.

3.2.16.1 *Discussion*—For relative BSDF measurements, the incident power is not measured directly. For absolute BSDF measurements it is important to verify the linearity, and if necessary correct for any nonlinearity, of the detector system over the range from the incident power level down to the scatter level which may be as many as 13 to 15 orders of magnitude lower. If the same detector is used to measure the incident power and the scattered flux, then it is not necessary to correct for the detector responsivity; otherwise, the signal from each detector must be normalized by its responsivity. In all cases, the absolute power is not needed, so long as the unit of power is the same as that used to measure the scattered power P_s.

3.2.17 *noise equivalent BSDF, NEBSDF, n*—the root mean square (rms) of the noise fluctuation expressed as equivalent BSDF.

3.2.17.1 *Discussion*—The noise equivalent BSDF is given by the DSF divided by cos θ_s. Because of the factor cos θ_s, the NEBSDF depends upon scattering angle and diverges to infinity at $\theta_s = 90°$. The NEBSDF is inversely proportional to the collection solid angle.

3.2.18 *noise equivalent DSF, NEDSF, n*—the root mean square (rms) of the noise fluctuation expressed as equivalent DSF.

3.2.18.1 *Discussion*—Measurement precision is limited by the acceptable signal to noise ratio with respect to these fluctuations. Unlike the NEBSDF, the NEDSF should be independent of scattering geometry and is evaluated by repeated measurements with the source beam blocked. The NEDSF is given by the rms of the repeated measurements divided by the incident power. The NEDSF is inversely proportional to the collection solid angle.

3.2.19 *photometric BSDF, n*—the sample luminance divided by the sample illuminance for a uniformly-illuminated and uniform sample.

3.2.20 *plane of incidence, PLIN, n*—the plane containing the sample normal and central ray of the incident flux.

3.2.21 *relative normalization method, n*—a method for performing a scattering measurement in which a diffusely reflecting sample of known BRDF is used as a reference.

3.2.22 *receiver, n*—a system that generally contains apertures, filters, focusing optics, and a detector element that gathers the scatter flux over a known solid angle and provides a measured signal.

3.2.23 *receiver solid angle,* Ω*, n*—the solid angle subtended by the receiver aperture stop from the center of the sampling aperture.

3.2.24 *sample coordinate system, n*—a coordinate system fixed to the sample and used to specify position on the sample surface.

3.2.24.1 *Discussion*—The sample coordinate system (*X, Y, Z*) is application and sample specific. The cartesian coordinate system shown in Fig. 3 is recommended for flat samples. The origin is at the geometric center of the sample face with the *Z* axis normal to the sample. A fiducial mark must be shown at the periphery of the sample; it is most conveniently placed along either the *X* or *Y* axes. If the sample fiducial mark is not an *X* axis mark, the intended value should be indicated on the sample. The incident and scatter directions are measured in the beam coordinate system (*XB, YB, ZB*). The *Z* and *ZB* axes are always the local normal to the sample face.

3.2.25 *sample irradiance,* E_e*, n*—the radiant flux incident on the sample surface per unit area.

3.2.25.1 *Discussion*—In practice, E_e is an average calculated from the incident power, P_i, divided by the illuminated area, *A*. The incident flux should arrive from a single direction; however, the acceptable degree of collimation or amount of convergence is application specific and should be reported.

3.2.26 *sample radiance,* L_e*, n*—a differential quantity that is the reflected radiant flux per unit projected solid angle per unit sample area.

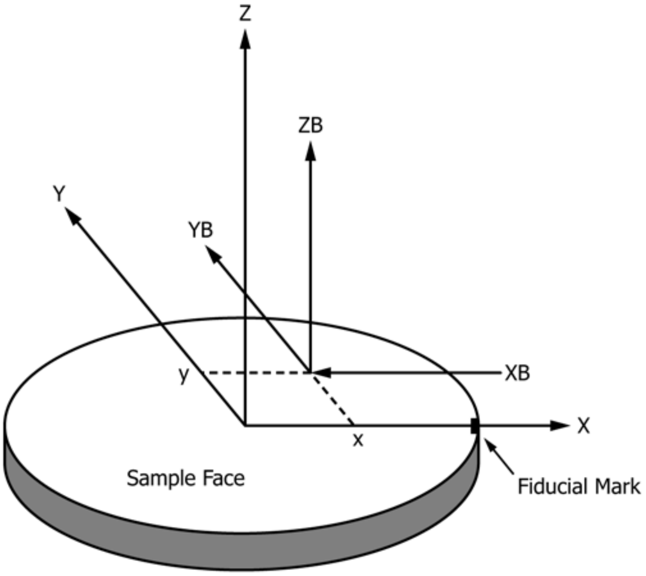
3.2.26.1 *Discussion*—In practice, L_e is an average calculated from the scattered power, P_s, collected by the projected receiver solid angle, $\Omega \cos\theta_s$, from the illuminated area, *A*. The receiver aperture and distance from the sample determines Ω and the angular resolution of the instrument.

3.2.27 *sampling aperture, n*—the smaller of either the illuminated area on the sample or the sample area within the receiver field-of-view.

3.2.28 *scatter, n*—the radiant flux that has been redirected over a range of angles by interaction with the sample.

3.2.29 *scatter azimuth angle,* φ_s*, n*—angle from the *XB* axis to the projection of the scatter direction onto the *X-Y* plane; see Fig. 1.

3.2.29.1 *Discussion*—See Discussion for *scatter polar angle*.



NOTE 1—The *X*, *Y*, and *Z* axes define the right-handed sample coordinate system centered at the geometric center of the sample face.

NOTE 2—The fiducial mark indicates the location of the positive *X* axis and can be on the edge or back of the sample.

NOTE 3—The *XB*, *YB*, and *ZB* axes define the right-handed beam coordinate system, are parallel to the *X*, *Y*, and *Z* axes, respectively, and are offset from the sample coordinates by coordinates *x* and *y* along the *X* and *Y* axes, respectively.

FIG. 3 Relationship Between Sample and Beam Coordinate Systems

3.2.30 *scatter direction, n*—the central ray of the collection solid angle of the scattered flux specified by θ_s and φ_s in the beam coordinate system.

3.2.31 *scatter plane, n*—the plane containing the central rays of the incident flux and the scatter direction.

3.2.32 *scatter polar angle,* θ_s, *n*—polar angle between the central ray of the scattered flux and the *ZB* axis; see Fig. 1.

3.2.32.1 *Discussion*—There is some ambiguity in the values of polar and azimuthal angles that needs explaining. What really uniquely defines a direction are the values $\sin(\theta)\cos(\varphi)$ and $\sin(\theta)\sin(\varphi)$, which are the *X* and *Y* coordinates, respectively, of the projection of the direction, expressed as a unit vector, onto the *X-Y* plane. Since $\sin(-\theta)\cos(\varphi+180°) = \sin(\theta)\cos(\varphi)$ and $\sin(-\theta)\sin(\varphi+180°) = \sin(\theta)\sin(\varphi)$, the change of variables $\theta \leftarrow -\theta$ and $\varphi \leftarrow \varphi + 180°$ does not change the direction. In many measurements, the scatter azimuthal angle is treated as fixed, while the scatter polar angle is allowed to be negative.

3.2.33 *source direction, n*—the central ray of the incident flux specified by θ_i and φ_i in the beam coordinate system, pointing from the sample to the illumination.

3.2.33.1 *Discussion*—The source direction is the opposite of the incident direction.

3.2.34 *specular direction, n*—the central ray of the reflected flux that lies in the PLIN with $\theta_s = \theta_i$ and $\varphi_s = \varphi_i + 180°$.

3.2.35 *specular normalization method, n*—a method for performing a scattering measurement in which the incident power is measured by measuring the light specularly reflected from a mirror of known reflectance.

4. Significance and Use

4.1 The angular distribution of scatter is a property of surfaces that may have direct consequences on an intermediate or final application of that surface. Scatter defines many visual appearance attributes of materials, and specification of the distribution and wavelength dependence is critical to the marketability of consumer products, such as automobiles, cosmetics, and electronics. Optically diffusive materials are used in information display applications to spread light from display elements to the viewer, and the performance of such displays relies on specification of the distribution of scatter. Stray-light reduction elements, such as baffles and walls, rely on absorbing coatings that have low diffuse reflectances. Scatter from mirrors, lenses, filters, windows, and other components can limit resolution and contrast in optical systems, such as telescopes, ring laser gyros, and microscopes.

4.2 The microstructure associated with a material affects the angular distribution of scatter, and specific properties can often be inferred from measurements of that scatter. For example, roughness, material inhomogeneity, and particles on smooth surfaces contribute to optical scatter, and optical scatter can be used to detect the presence of such defects.

4.3 The angular distribution of scattered light can be used to simulate or render the appearance of materials. Quality of rendering relies heavily upon accurate measurement of the light scattering properties of the materials being rendered.

5. Apparatus

5.1 Instruments designed to measure the angular distribution of scattered light consist of three basic elements: an illuminator containing a directed source of optical radiation, a means for positioning a sample, and a receiver to collect and measure the scattered light. These components are described in a general manner so as to not exclude any particular type of scatter instrument. The three components are connected in a manner that allows for selection of an incident direction and the collection of flux in a scattered direction. However, not all instruments allow control over all four angles ($\theta_i,\varphi_i;\ \theta_s,\varphi_s$). For example, it is common to have ($\theta_i;\ \theta_s$) positioning, only. Due to the wide variability of instrument designs and capabilities, specific parameters, noted below, should be identified and reported with any result.

5.1.1 *Illuminator,* containing the source and associated optics to produce irradiance on the sample. If a broad band source or tunable laser is used, the bandwidth and wavelength selection technique should be specified. If a broad band source is used, its spectral power distribution should be reported. If a laser source is used, the laser type and its center wavelength should be reported.

5.1.1.1 A source monitor may be used to correct for fluctuations in the source. It should be located as far downstream in the optical path as practicable, without contributing unreasonably to system scatter, so as to capture all possible sources of fluctuations or drift. The source monitor should be sufficiently insensitive to changes in beam properties, such as spatial mode or polarization, and not have any band sensitivities that would yield undue sensitivities to wavelength.

5.1.1.2 The beam should be collimated or slightly converging. Laser-based instruments often use a converging beam with f-number greater than f/20 focused at the receiver in order to achieve high angular resolution in the scatter direction for measurements near the specular beam or diffraction peaks. A converging beam focused at the sample location may be used if spatial resolution is important. If the convergence angle is small, the uncertainty introduced by a non-unique angle of incidence is usually negligible. A collimated source may be used for systems that do not require high angular or sample position resolution. It is the user's responsibility to assure that any spread in θ_i does not compromise the results. The degree of convergence of the incident beam generally has a direct influence on the instrument signature.

5.1.1.3 Good reduction of the instrument signature requires careful baffling around the source assembly to limit off-axis light. For laser sources, a spatial filter is often used as the last optical element before the final focusing or collimating element. The final mirror or lens which directs light to the sample should have low scatter, since it contributes directly to small angle scatter in the instrument signature.

5.1.1.4 A means should be provided for controlling the polarization state of the incident flux as this can impact the measured BSDF. Orthogonal source polarization components (parallel, or *p*, and perpendicular, or *s*) are defined by the direction of the electric field relative to the PLIN. If results for unpolarized light are desired, then it is often best to perform two measurements, using *p* and *s* polarized light, with the average being reported. A complete polarimetric description of the BSDF requires the Mueller matrix formalism; however, Mueller matrix BSDF measurements are beyond the scope of this standard.

5.1.1.5 For measurements performed in the plane of incidence, it is sometimes possible to obtain results equivalent to those using unpolarized light by using either 45°-polarized incident light or circularly polarized incident light. However, since this practice is not valid under all conditions, it is the responsibility of the user to determine if such practice is valid for the sample being studied.

5.1.1.6 Absorbing samples may be heated by the incident flux, which may change their scatter characteristics, mechanically distort them, or burn them. Special care must be taken with high-power laser or infrared sources on absorbing samples.

5.1.1.7 The source light may be modulated electronically or by a chopper wheel in order to enable synchronized phase-sensitive lock-in detection of the scattered signal.

5.1.1.8 The profile of the illuminated spot on the sample should be reported in order to assess the spatial resolution of the instrument. If the sample is under-illuminated, the size of the illuminated spot must be smaller than the receiver field of view. Even if high spatial resolution is not needed by the user, if the illumination spot is too small, then features in the data may be a result of variations or inhomogeneities in the specimen, rather than a measure of the average properties of the material. For the case of coherent illumination, the size of the illuminated spot will have an effect on the speckle statistics.

5.1.1.9 For broad band sources, the spectral characteristics of the source may be very important. It may be necessary to report the amount of light which is not contained within the nominal bandwidth of the source.

5.1.2 *Sample Holder*—The sample holder should provide a secure mount for the sample that does not introduce any warp, and allows the sample to be placed with its fiducial marks in a particular, known orientation with respect to the beam geometry. The rotation axes of the stages that achieve the ($\theta_i,\varphi_i;\ \theta_s,\varphi_s$) positioning must be relative to the sample front surface; this can be accomplished by orienting the sample holder, source, or receiver assemblies, or combination thereof. Some sample mounts incorporate linear positioning stages that allow measurements at multiple spots on the specimen surface. The sample mount must be kept unobtrusive so that it does not block the incident or scattered light, or contribute stray flux to the instrument signature.

5.1.2.1 Since the measurement needs to be done with respect to the front surface of the specimen, it is often necessary to provide manual positioning (Z-motion) to accommodate different sample thicknesses, and to orient the sample (tilt in two directions) with respect to the incident beam. It is good practice to check that the incident beam stays on the center of the sample when configured in a near grazing angle, and that when the source is incident in the normal direction that the sample reflects light back to the source.

5.1.3 *Receiver Assembly*—If the system design includes degrees of freedom at the receiver for achieving the scatter direction, then the receiver assembly should normally have provisions for rotating about an axis on the front face of the sample in order to vary θ_s. If measurements out of the PLIN are required, the receiver assembly may also rotate out of the PLIN. This capability may also be provided by pitch, yaw, and roll of the sample, but it becomes more difficult to capture and dump the specularly reflected beam.

5.1.3.1 *The Receiver Acceptance Aperture:*

(1) The acceptance aperture defines the receiver solid angle, Ω, which is used in the BSDF calculation and defines the

angular resolution. There can be an exception to the requirement that Ω be well known if the relative normalization method is used. In that case it is the user's responsibility to ensure that the system parameters remain constant between measurements. For many systems, where there are no optical elements between the sample and the solid angle defining aperture, the receiver solid angle is given by:

$$\Omega \cong \frac{A_{\text{rec}}}{r^2} \quad [\text{sr}] \tag{9}$$

where A_{rec} is the area of the receiver aperture, and r is the distance of that aperture from the illuminated region of the sample. The approximation in Eq 9 is valid to better than 1 % when Ω is less than 0.04 sr.

(2) For transparent or translucent samples, there can be a range of distances r between the receiver and the scatterers. Therefore, one must include this variability in the uncertainty of Ω.

(3) If the acceptance aperture is too small and a coherent source is used to irradiate the sample, speckle may cause strong, unpredictable variations in the scatter. If speckle effects contribute unacceptably to the results, they can be reduced by averaging over a large number of measurements at different sample locations, or by moving or rotating the sample while the measurement is being performed. It is the user's responsibility to ensure that BSDF features are not due to speckle.

(4) The user may wish to employ a variable aperture to trade sensitivity for angular resolution when measuring specular surfaces, since best angular resolution is needed near the specular direction where BSDF has a steep slope. Best sensitivity is needed at larger angles where BSDF might approach the NEBSDF.

(5) If either the absolute normalization method or the specular normalization method is used, then an aperture should be available which is larger than the size of the incident beam at that aperture. Otherwise, some of the incident light will not be accounted for by the incident power measurement.

5.1.3.2 *The Receiver Field of View:*

(1) The field of view shall include the entire irradiated area, A. The field of view of the receiver will determine if all of the light scattered by a specimen into the solid angle defined by the receiver is detected. If the field of view is smaller than the illuminated spot on the specimen, or if it is misaligned with respect to the center of the illuminated spot on the sample, then not all light will be collected, and an erroneous result will be obtained, which is not obvious to the operator. It is recommended that the field of view at the sample plane be characterized.

(2) If the sample is diffusive or translucent, then some light will be radiated from locations away from the irradiated spot. Therefore, the field-of-view must be larger than the illumination spot to assure that any diffusively scattered light is captured by the receiver.

(3) When the incident angle is large, the irradiated area becomes elongated. The field-of-view must be large enough to accommodate the largest angle of incidence that will be used during a measurement.

(4) A recommended method for measuring the receiver field of view is to locate a small moveable diffuse light source in the X-Y plane, while measuring the receiver signal in the Z direction. The signal should remain constant over an area larger than the illuminated spot, keeping in mind that the illuminated spot elongates as the incident angle is increased. Choosing a tolerance level T, the lengths of the field of view, $l_{\text{FOV},x}$ and $l_{\text{FOV},y}$ in the X and Y directions for which the signal remains within a fraction T of the maximum signal should be determined. The values of $l_{\text{FOV},x}$ and $l_{\text{FOV},y}$ should be recorded together with the tolerance level used. It is useful to perform the same measurement in other sample-receiver orientations, as well, in order to verify that the field of view is always aligned on the center of the sample.

(5) The receiver field of view is affected by the design of the receiver as well as the uniformity of the detector element. Performing a measurement of the field of view profile ensures that detector non-uniformities do not contribute to the results.

5.1.3.3 *The Receiver Detector:*

(1) The receiver detector (and any associated electronics) should be linear over the entire signal range of the measurement. The receiver and preamplifier must be calibrated together over their useful operating range. A calibration curve showing relative optical power versus measured signal must be obtained for each preamplifier gain setting. Operating regimes are selected for each gain setting to avoid saturating the detector while remaining on a low gain setting. The source monitor should also be calibrated in the same way, although the dynamic range need not be very wide.

(2) The receiver detector should have uniform sensitivity over its area. If the detector is not uniform, an integrating sphere or other non-imaging optic can be used to ensure that the sensitivity of the receiver is uniform over the receiver field of view.

(3) If a broad band source is used in the measurement, the spectral sensitivity of the detector may affect the measurement.

(4) The temporal response of the detector (and any associated electronics) should be significantly faster than the timescale of the measurement. If the source is modulated, the detector must be able to respond to the modulation.

(5) It may be necessary to use an optical bandpass filter on the detector to minimize acceptance of background light.

5.1.3.4 *Receiver Optics*—There may be optics (lenses or mirrors) in the beam path between the sample and the receiver detector. Any optics between the sample and the receiver acceptance aperture, however, can have an adverse effect on the instrument signature. Furthermore, such optics can have an adverse effect on the accuracy of the collection solid angle Ω. Optics between the receiver acceptance aperture and the receiver detector are often useful for controlling the light and defining the field of view of the detector. If the absolute normalization or specular normalization method is used, then all optics must be kept clean in order to minimize variations in the collection sensitivity over the collection solid angle.

5.1.3.5 Since scatter may alter the polarization state of the light, complete characterization of scatter requires measurements with a polarization analyzer at the receiver. Since many applications do not require such detailed characterization, the receiver in such systems should either be shown to be polarization insensitive or be capable of measuring two orthogonal polarization states.

5.2 Correct alignment of the source, sample, and receiver assemblies is essential for accurate BSDF measurements. A subtle error that can be introduced by misalignment occurs when the receiver does not rotate about the sample face. The receiver field-of-view will "walk off" the illuminated area and the measured signal is then lower than it should be. Although it is not necessary to perform a total system alignment every day, alignment should be verified on a daily basis for movable components.

5.3 *Ancillary Elements*—Other elements of the instrument design are important for optimizing the instrument for specific types of measurements.

5.3.1 *Stray Light Control*—It is important to reduce any stray light in the instrument. For example, trapping any specular reflection from the sample can reduce the signal that results from lab/instrument reflections. Examples of beam dumps are black flocked paper, a razor blade stack, absorbing glass plates, or a tapered blackened glass tube. An absorbing enclosure around the instrument can sometimes be sufficient for this purpose.

5.3.2 The efficacy of the stray light reduction method in a system can be determined by assessing the quality of the instrument signature. If the DSF instrument signature is greater than the NEBSDF of the instrument and greater than that expected for Rayleigh scatter in the air, then there is a good chance that stray light is the culprit.

5.3.3 *Contamination Control*—Any contamination or other damage to the sample can result in elevated values of the BSDF. For optically smooth surfaces, the instrument must be housed in a suitably clean environment so that specimens will not become contaminated during the measurement, or during specimen handling. For ultra-low scatter measurements, it is also necessary to provide clean particle-free air to reduce the instrument signature. Lastly, care should be taken to ensure that the air does not contain chemical vapors that can deposit films onto or absorb into samples.

5.4 The appendix provides some generic optical designs for source and receiver combinations, with discussions of their merits and faults.

6. Calibration and Normalization

6.1 *General*—Instrument calibration is often confused with measurement of P_i. Calibration of a BSDF instrument involves systematic standardization and verification of its quantitative results. Incident power must be measured for correct normalization of the scattered power. Absolute measurement of powers is not required as long as the P_s/P_i ratio is correctly measured. Alternatively, a reference sample can be used as a normalization reference.

6.2 *Calibration*—Calibration in a BSDF measurement consists of accurately determining the incident power, the scattered power, the detector solid angle, and the scattering angle.

6.2.1 *Incident and Scattered Power Measurement*—Since the measurement depends upon ratios of incident and scattered power measurement, calibration of the power measurements requires validation that the detection system (detector and electronics) is linear over the dynamic range of the measurement and that the signal is zero when no light is incident on the detector.

6.2.2 *Detector Solid Angle*—The value of the detector solid angle is required if the either the absolute or relative specular reflectance methods are used for normalization. This requires a value for the aperture area and the distance of the aperture from the illuminated spot on the sample.

6.2.3 *Scattering Angle*—In most cases, calibration of the scattering angle requires accurate alignment of the instrument.

6.2.4 A full system calibration is not required on a daily basis, but the system should be checked daily. This check can be accomplished by measuring the instrument signature and a stable reference sample that provides data over several decades. Changes from past results are an indication of calibration problems and the cause of the change must be determined. It is good operating practice to maintain a reference sample at the scatter facility for this calibration check. Recalibration must be accomplished when components are changed, repaired or realigned. Include a data file number for the most recent reference sample measurement with every set of BSDF data as a record of instrument response in case the data set is questioned at a later time.

6.3 *Normalization*—There are four acceptable methods for normalizing the scattered power to the incident power. Each method is dependent on different measured parameters. If attenuating filters are used to extend the dynamic range of the instrument, they must be calibrated for each condition, and their presence included in the calibration.

6.3.1 *Absolute*—An absolute normalization is made by moving the receiver assembly onto the optical axis of the source, without the source beam striking the sample (for example, with either no sample in the sample holder or the sample moved to one side). *This method requires that the receiver detector and its associated electronics be linear or be linearized over a very wide dynamic range*. The entire incident beam must enter the receiver assembly and the signal V_i and the monitor signal V_{mi} are recorded. If the unsaturated detector response is $s(\lambda)$, then the incident power is:

$$P_i = \frac{V_i s(\lambda)}{V_{im}} \tag{10}$$

As will be seen later, it is not necessary to know $s(\lambda)$ for the sample BSDF calculation so long as it remains constant.

6.3.2 *Relative*—A relative normalization is made by measuring a reference sample that has a known BSDF in a specific geometry. *This method depends on knowing the reference sample BSDF in that geometry and at the measurement source wavelength and polarization.* This reference sample is usually a high reflectance, diffuse material. The reference sample should be spatially uniform, isotropic, and relatively insensitive to geometry. Such samples are available from a number of sources. The reference sample is inserted in the sample holder, the system is configured to the geometry to which the BSDF is known (BSDF_r, at a specific scattering angle θ_{sr}), and a detector signal, V_r, and a monitor signal, V_{rm}, are recorded. The incident power can be shown to be:

$$P_i = \frac{V_r s(\lambda)}{\mathrm{BSDF}_r V_{rm} \Omega \cos \theta_{sr}} \quad (11)$$

As will be seen later, it is not necessary to know Ω or $s(\lambda)$ for the sample BSDF calculation, so long as they remain constant.

6.3.2.1 It is good practice to check that the reference signal does not depend upon location of the irradiance onto the reference sample. Variation in this signal can result from speckle (in the case of coherent illumination), the use of an illumination spot smaller than that for which the reference sample was intended, or contamination or aging of the reference sample. In some cases, use of the average signal obtained from multiple locations on the reference sample will suffice. It is the operator's responsibility to ensure that any variation is not the result of sample contamination or aging.

6.3.3 *Specular*—An alternative relative normalization can be made with a specular reference sample having a known specular reflectance, R_r. Like the absolute normalization method, it generally requires that the receiver system have a very wide dynamic range. It is useful for systems whose sample holder is opaque and cannot be moved out of the beam, or for systems whose range of motion does not allow the detector to view the incident beam. It is also useful for sources which overfill the sample, in which case the reference must be the same size as the sample.

6.3.3.1 Insert the specular reference sample in the sample holder. Ensure that the specular beam is entirely collected by the receiver (that is, use a sufficiently large receiver aperture) and measure the signal, V_r, and the monitor signal V_{rm}. The incident power is given by:

$$P_i = \frac{V_r s(\lambda)}{V_{rm} R_r} \quad (12)$$

It is not necessary to know $s(\lambda)$ for the sample BSDF calculation so long as it remains constant.

6.3.4 *Diffuse Reflectance*—This method of normalization requires that a relative, un-normalized BSDF, BSDF_{rel}, be measured at many scatter directions covering the geometry corresponding to an integrated reflectance or transmittance measurement. *This method requires a separately measured integrated reflectance or transmittance* ρ. The BSDF is then normalized using:

$$\mathrm{BSDF} = \frac{\rho \mathrm{BSDF}_{rel}}{\rho_{rel},} \quad (13)$$

where the factor ρ_{rel} is calculated by integrating the relative BSDF over the set of directions $\{\theta_s, \varphi_s\}$ captured by the integrated reflectance measurement:

$$\rho_{rel} = \iint_{\{\theta_s, \varphi_s\}} \mathrm{BSDF}_{rel} \cos\theta_s \sin\theta_s \, d\theta_s \, d\varphi_s \quad (14)$$

6.3.4.1 Examples of integrated scatter measurements that may be used for this method include the directional hemispherical reflectance described in Test Method E1331, a directional conical reflectance described in Nicodemus (1977), and total scatter described in ISO 13696.

6.3.4.2 This method is most useful for reference samples in conditions where the illumination must overfill the sample, such as for small samples or large incident angles.

6.3.4.3 It is the responsibility of the operator to ensure that the relative BSDF has been measured over a sufficiently fine grid, that the directions include all of the solid angle included by the integrated reflection measurement, that the conditions (for example, polarization, wavelength, and incident angle) were the same in the BSDF measurement as for the integrated reflectance measurement, and that the correct Jacobian is used to transform the differentials $d\theta_s \, d\varphi_s$ to differentials of the scan coordinates used in the measurement.

7. Procedure

7.1 Sample cleanliness can be a significant factor in the scatter level. The user should adopt a procedure for cleaning samples prior to measurement and this cleaning procedure should be reported with the BSDF results.

7.2 Correct alignment of the source, sample, and receiver are essential for accurate BSDF measurements. A typical example of a subtle error that can be introduced by misalignment occurs when the receiver does not rotate in θ_s about the sample face. The receiver field-of-view will "walk off" the illuminated area, *A*, and the measured BSDF will be lower than actual BSDF as θ_s increases. Although it is not necessary to perform a total system alignment every day, alignment should be verified on a daily basis for movable components.

7.3 Measure the incident power using one of the four normalization methods described above.

7.4 After cleaning the sample and verification of alignment, the sample is inserted in the sample holder. The detector voltage, V_s, and the source monitor voltage, V_{sm}, are recorded for each parameter set of interest. For example, BSDF measured in the plane-of-incidence requires changing θ_s while holding other parameters constant. The measurement results consist of three columns of data for θ_s, V_s, V_{sm}. The constant parameters, θ_i and φ_s, are retained in the header information for this data set. Post processing is used to calculate BSDF and express the results in the desired tabular or graphical format, but we can calculate P_s at this time. In this calculation, the ratio of source monitor voltages is included to correct for variation of source intensity.

$$P_s = \frac{V_s s(\lambda)}{V_{sm}} \quad (15)$$

7.5 BSDF can exhibit strong sensitivity to azimuthal orientation, spot size and position changes on the sample face. Good operating practice dictates checking for sensitivity to these and other system parameters.

8. Calculation

8.1 The BSDF of an unknown sample is calculated at each incident and scattered direction from the following relationship:

$$\mathrm{BSDF} = \frac{P_s}{P_i \Omega \cos \theta_s} \quad [\mathrm{sr}^{-1}] \quad (16)$$

The value of P_i is determined by the normalization method used. The correct angular variables may also be calculated in post processing with BSDF. In all cases θ_i and θ_s are referenced to the sample normal.

8.1.1 For the *absolute normalization method*, the BSDF is given by:

$$\mathrm{BSDF} = \frac{V_{\mathrm{im}} V_{\mathrm{s}}}{V_{\mathrm{sm}} V_{\mathrm{i}} \Omega \cos \theta_{\mathrm{s}}} \quad [\mathrm{sr}^{-1}] \tag{17}$$

8.1.2 For the *relative normalization method*, the BSDF is given by:

$$\mathrm{BSDF} = \frac{V_{\mathrm{s}} V_{\mathrm{rm}} \cos\theta_{\mathrm{sr}}}{V_{\mathrm{r}} V_{\mathrm{sm}} \cos\theta_{\mathrm{s}}} \mathrm{BSDF}_{\mathrm{r}} \quad [\mathrm{sr}^{-1}] \tag{18}$$

8.1.3 For the *specular normalization method*, the BSDF is given by:

$$\mathrm{BSDF} = \frac{V_{\mathrm{rm}} V_{\mathrm{s}} R_{\mathrm{r}}}{V_{\mathrm{sm}} V_{\mathrm{r}} \Omega \cos \theta_{\mathrm{s}}} \quad [\mathrm{sr}^{-1}] \tag{19}$$

8.1.4 For the *integrated reflectance normalization method*, the relative BSDF is given by:

$$\mathrm{BSDF}_{\mathrm{rel}} = \frac{V_{\mathrm{s}}}{V_{\mathrm{sm}} \Omega \cos \theta_{\mathrm{s}}} \tag{20}$$

Eq 13 and 14 are then used to calculate the absolute BSDF.

8.2 Many facilities prefer to store only raw data and calculate BSDF and display variables as required to produce a graph or data table. If data are sent to another facility, it is essential to convert to BSDF and the angular variables defined in this practice.

9. Report

9.1 BSDF data is expressed in tabular or graphical format as a function of the variable parameter. For BSDF data that spans many decades, such as that measured from specular samples, the data should be expressed in scientific notation or plotted on a logarithmic scale.

9.2 There is a considerable amount of information that should accompany BSDF measurements. These can be categorized as those which are required, recommended, and optional. Any parameter which is varied during the measurement should be indicated as such, for example, by labeling the data columns. Other information can be contained in a data file header or in another associated file or document. Some of these parameters may be specific values, while some may be descriptive phrases or prose.

9.3 *Required Information*—The following information shall be defined for each measurement:

9.3.1 Description of the sample (size, shape, color, finish, condition, markings or identification, etc.),

9.3.2 Any treatment performed on the sample before measurement,

9.3.3 Angle of incidence,

9.3.4 Incident azimuth angle,

9.3.5 Scatter polar angle,

9.3.6 Scatter azimuth angle,

9.3.7 Location of measurement on sample,

9.3.8 Wavelength,

9.3.9 BSDF or DSF (specify), and

9.3.10 Incident polarization.

9.4 *Recommended Information*—The following information is recommended to be included with each measurement:

9.4.1 Polarization sensitivity of receiver,

9.4.2 Instrument signature,

9.4.3 Normalization method,

9.4.4 Identification of any reference samples,

9.4.5 NEBSDF or NEDSF (specify),

9.4.6 Illumination spot size and profile,

9.4.7 Convergence of the illumination,

9.4.8 Source spectral bandwidth,

9.4.9 Uncertainty associated with the measurement,

9.4.10 The receiver field-of-view and profile,

9.4.11 Measurement date and time,

9.4.12 Laboratory information (name, location, and contact),

9.4.13 Operator information (name, location, and contact), and

9.4.14 Instrument name or model.

9.5 *Optional Information*—The following information can be optionally included, unless they are believed to be important to the application or are set to an unusual configuration:

9.5.1 Pressure, temperature, and humidity in the room or of the sample, and

9.5.2 Documentation establishing the linearity of the receiver detection system.

10. Keywords

10.1 bidirectional reflectance distribution function (BRDF); bidirectional scatter distribution function (BSDF); bidirectional transmittance distribution function (BTDF); diffuse; irradiance; radiance; scatter; specular

APPENDIXES

(Nonmandatory Information)

X1. REVIEW OF OPTICAL DESIGNS

X1.1 This section describes a few generic optical designs for the source and receiver assemblies. All of the drawings are shown in a transmission configuration with no aspecular angle. In order to further simplify the drawings, all focusing or de-focusing optics are shown as lenses; any lens may be replaced with a curved mirror, which in many cases is advisable since mirrors are more achromatic and can be produced with lower scatter tolerances.

X1.2 Fig. X1.1(1) shows an optical design which begins with an aperture A forming either a lamp source, an exit slit of a monochromator, or an aperture of a spatial filter. The rays leaving aperture A are diverging and are recollected by focusing optic B. The rays between optic B and the receiver aperture C can be collimated or converging. The convergence can be such that the beam is focused at the aperture C or at the sample. The area of receiver aperture C and its distance from the sample determine the solid angle of collection Ω. A focusing optic D images the sample onto a field-stop E. The size of the field-stop E determines the field-of-view of the receiver. The detector F lies behind the field-stop E. This optical design is the most common design for those using the absolute normalization method, since the information needed to calculate Ω is readily available, with the fewest parameters. It is also the most common design for laser-based

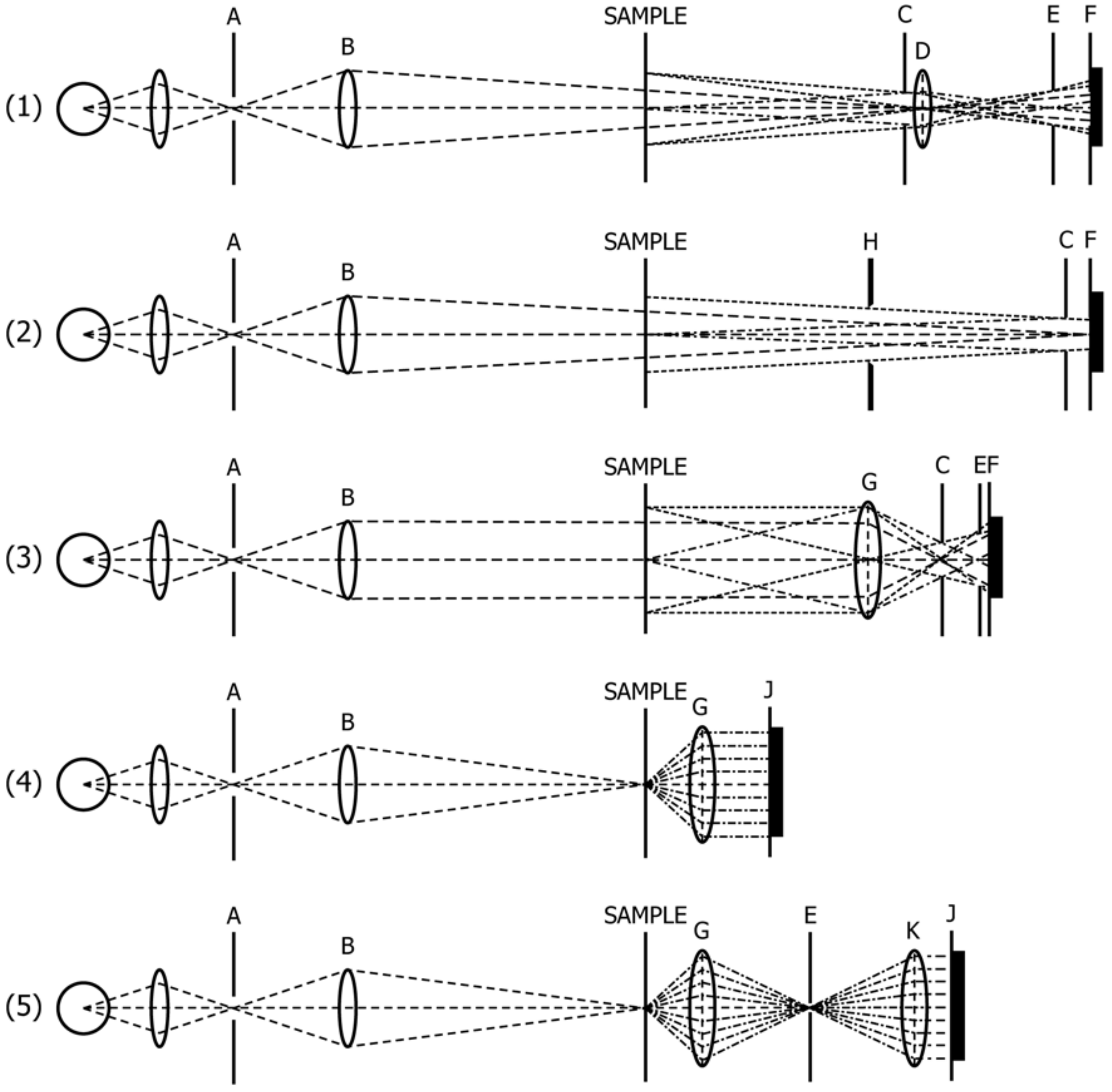


FIG. X1.1 Schematics of Optical Designs for BSDF Measurements

measurements, because it has the fewest sources of stray light, and because the low divergence of the laser does not require additional optics to control it.

X1.3 Fig. X1.1(2) shows a variation on the design shown in Fig. X1.1(1). The main difference in the design is the lack of optic D and aperture E, which together define the receiver field-of-view. Instead, the field-of-view is defined by one or more baffles H. The detector is immediately behind the solid-angle-defining aperture C. This design has the advantage that it is relatively easy to ensure that the detection efficiency over the collection solid angle is uniform, since there is no optic past the sample and the detector F can incorporate an integrating sphere to guarantee uniformity. The disadvantage of this system is that the field of view must be large, and the baffling can cause stray light problems, especially when laser sources are used for small angle scattering. The baffling can be eliminated altogether, but then the field of view is so large that stray light can become a problem.

X1.4 Fig. X1.1(3) shows another optical design whose receiver incorporates an extra focusing optic G before the receiver aperture C. The optic G is designed to image the source aperture A onto receiver aperture C, providing the instrument with high angular resolution for highly collimated incident light, and to image the sample onto aperture E, so that aperture E defines the receiver field-of-view. This optical design can have a fairly high angular resolution for incoherent light sources. However, the presence of the optic G between the sample and the receiver aperture C makes it difficult to accurately measure the solid-angle Ω. Furthermore, scatter in the optic G can adversely affect the instrument signature in small-angle scattering applications.

X1.5 Fig. X1.1(4) and Fig. X1.1(5) describe optical designs for systems which incorporate an imaging detector J located at the back focal plane of a collecting optic G. The design shown in Fig. X1.1(4) has no field-of-view defining aperture, while the design shown in Fig. X1.1(5) has an aperture E and second lens K to limit the field-of-view. The advantage of such a system is that the BSDF can be measured extremely rapidly. However, the system can suffer from a number of stray light issues, angular inaccuracies, and radiometric inaccuracies.

X2. OTHER DATA REPRESENTATIONS

X2.1 It some applications, it is useful to present the light scattering function in an alternative fashion than the BSDF. In this appendix, several other representations are given.

X2.2 *Photometric BSDF*—The photometric BSDF is the average of the BSDF weighted by a specific illuminant and response function. It is given by:

$$\mathrm{BSDF}_{\mathrm{photo}} = \frac{\int_{\lambda} \mathrm{BSDF}(\lambda)S(\lambda)V(\lambda)d(\lambda)}{\int_{\lambda} S(\lambda)V(\lambda)d(\lambda)} \qquad (\mathrm{X2.1})$$

where BSDF(λ) is the spectral dependence of the BSDF, $S(\lambda)$ is the spectral power distribution of the illuminant, and $V(\lambda)$ is the spectral luminous efficiency. The specific illuminant (for example, CIE Standard Illuminant D65) and response [for example, photopic $V(\lambda)$] must be specified with any data. In Eq X2.1, the bidirectional dependence of the BSDF, as well as dependence upon position, is not given explicitly.

X2.3 *Colorimetric BSDF*—The angular dependence of the color of a material can be expressed in terms of a colorimetric BSDF. Using the CIE color matching functions [$\bar{x}(\lambda)$, $\bar{y}(\lambda)$, and $\bar{z}(\lambda)$] for one of the CIE standard colorimetric observers and a CIE standard illuminant $S(\lambda)$, the colorimetric BSDF is defined as:

$$\mathrm{BSDF}_{\mathrm{color},X} = k\int_{\lambda} \mathrm{BSDF}(\lambda)S(\lambda)\bar{x}(\lambda)\mathrm{d}(\lambda) \qquad (\mathrm{X2.2})$$

$$\mathrm{BSDF}_{\mathrm{color},Y} = k\int_{\lambda} \mathrm{BSDF}(\lambda)S(\lambda)\bar{y}(\lambda)\mathrm{d}(\lambda) \qquad (\mathrm{X2.3})$$

$$\mathrm{BSDF}_{\mathrm{color},Z} = k\int_{\lambda} \mathrm{BSDF}(\lambda)S(\lambda)\,\bar{z}(\lambda)\mathrm{d}(\lambda) \qquad (\mathrm{X2.4})$$

where the integration is carried out over the entire wavelength region in which the color-matching functions are defined, 360 nm to 830 nm (see Practice E308). The bidirectional dependence of the BSDF, as well as dependence upon position, is not given explicitly. The normalizing factor k is defined as:

$$k = \left(\int_{\lambda} S(\lambda)\,\bar{y}(\lambda)\mathrm{d}\lambda\right)^{-1} \qquad (\mathrm{X2.5})$$

The results can be expressed in any of the various color coordinates, such as CIELAB or CIELUV, so long as all the necessary information to interpret the results are included and the luminance factor represents the photometric BSDF. The colorimetric BSDF will depend upon the specific illuminant and observer used in the calculation.

X2.4 *Differential Scattering Function*—Presenting the DSF is equivalent to presenting the BSDF, since there is a direct relationship between the two: DSF = $\cos\theta_s$ BSDF. The advantage of the DSF representation is that the DSF, the DSF instrument signature, and the noise equivalent DSF do not have anomalous behavior for grazing viewing angles.

X2.5 *Directional Reflectance Factor*—The directional reflectance factor R_d is the BRDF normalized by the BRDF of a perfectly diffuse reflector [BRDF = $1/\pi$] and is given by $R_d = \pi$ BRDF. Color is often calculated from directional reflectance factor (see Practice E308).

X3. DATASET DESCRIPTION

X3.1 It is difficult to develop a uniform standard for what comprises a complete dataset, since different applications have different requirements. A truly complete dataset, even for a single wavelength and even if the resolution and data spacing were to be adapted to the changing BSDF, if one were to include all possible incident and scattering geometries, would take a daunting amount of time to acquire.

X3.2 In many cases interpolation schemes can be developed for specific applications, based upon physical models, to help to reduce these requirements. For example, if one knows that the scattering is due entirely to a rough surface in one of a couple limiting cases, then a simple single-wavelength in-plane measurement yields sufficient information to predict the scattering in all other geometries and wavelengths. However, in general, one cannot rely upon being in such a situation, and it is necessary to perform more measurements than that. In other applications, only a few geometries can be shown to suffice for a specific type of sample for quality control applications.

X3.3 It is useful, however, to develop a nomenclature that enables people to communicate their needs. The following terms are suggested for describing a BSDF dataset:

X3.3.1 *simple, adj—in describing a BSDF measurement*, having a single incident angle.

X3.3.2 *compound, adj—in describing a BSDF measurement*, having been performed using multiple incident angles.

X3.3.3 *one-dimensional, adj—in describing a BSDF measurement*, having the scattering direction scanned along a single coordinate.

X3.3.4 *two-dimensional, adj—in describing a BSDF measurement*, having the scattering direction scanned along two different coordinates.

X3.3.5 *in-plane, adj—in describing a BSDF measurement*, having the scattering direction scanned one-dimensionally in the plane of incidence.

X3.3.6 *azimuth-conical, adj—in describing a BSDF measurement*, having the scattering direction scanned one-dimensionally in a right-circular cone about the *Z* direction, with a fixed θ_s, varying φ_s.

X3.3.7 *diffractive-conical, adj—in describing a BSDF measurement*, having the scattering direction scanned one-dimensionally in a cone about an axis, that axis being along some direction in the surface plane.

X3.3.7.1 *Discussion*—A diffraction grating, oriented at an arbitrary angle with respect to an incoming beam will send its diffraction peaks into a right-circular cone whose axis is aligned with the rulings and which includes the specular direction. Thus a diffractive-conical BSDF measurement will scan through such diffractive orders. Using the two-dimensional grating equation, such a scan can be parameterized by:

$$\theta_s = \arcsin\left[\sqrt{(\sin\alpha\sin\beta - \sin\theta_i\cos\varphi_i)^2 + (\sin\alpha\cos\beta - \sin\theta_i\sin\varphi_i)^2}\right] \quad (X3.1)$$

$$\varphi_s = \arctan[\sin\alpha\cos\beta - \sin\theta_i\sin\varphi_i, \sin\alpha\sin\beta - \sin\theta_i\cos\varphi_i]$$

where α is the scan angle and β is a fixed constant corresponding to the orientation angle of the grating. The two-argument arctan(y,x) returns the angle of the coordinate (x,y).

X3.3.8 *spherical, adj—in describing a BSDF measurement*, having the scattering direction varied two-dimensionally in a manner that attempts to encompass the entire scattering sphere, in both reflection and transmission.

X3.3.9 *hemispherical, adj—in describing a BSDF measurement*, having the scattering direction varied two-dimensionally in a manner that attempts to encompass an entire scattering hemisphere, either in reflection or in transmission.

X3.3.10 *quarterspherical, adj—in describing a BSDF measurement*, having the scattering direction varied two-dimensionally in a manner that attempts to encompass half of the scattering hemisphere, either in reflection or in transmission, where the boundary of the nominal solid cone includes the sample plane and the plane of incidence.

X3.3.10.1 *Discussion*—For samples that are expected to be isotropic, a full hemispherical measurement may not be required. Instead, one can perform a quarterspherical measurement, and assume that the opposing quartersphere has an identical BSDF.

X3.3.11 *single wavelength, adj—in describing a BSDF measurement*, performed using only a single wavelength.

X3.3.12 *multi-wavelength, adj—in describing a BSDF measurement*, performed using a few to several discrete wavelengths, where the spacing between wavelengths does not give sufficient information to reliably interpolate between them, or that the spectral bandwidth of each bandpass did not overlap.

X3.3.13 *spectral, adj—in describing a BSDF measurement*, performed using a continuously-variable wavelength source, where each spectral band overlaps with adjacently measured spectral bands.

X3.3.14 *colorimetric, adj—in describing a BSDF measurement*, performed spectrally over the range from 360 nm to 830 nm with 20 nm or better resolution.

X3.3.15 *photometric, adj—in describing a BSDF measurement*, performed using a broadband source corresponding to a standard illuminant and using a detector having a photopic response function.

X3.3.16 *spatially-resolved, adj—in describing a BSDF measurement*, performed on multiple, well-defined, locations on the sample.

X3.3.17 *equi-spaced, adj—in describing a BSDF measurement*, performed such that the scattering coordinates were varied in equal spaced steps.

X3.3.17.1 *Discussion*—The scattering coordinates can consist of the angles θ_s or φ_s, or they can be other coordinates that are more specific to the application. For example, to perform a diffractive-conical measurement, the scattering coordinate will not be θ_s or φ_s, but will be either α or $\sin \alpha$. Another likely situation is for the measurement to be performed equi-spaced logarithmically on the aspecular angle α. In all cases, the scattering coordinates should be identified.

X3.3.18 *adaptively-spaced, adj—in describing a BSDF measurement*, performed such that the scattering coordinates are varied in a manner which depends upon the presence of structure in the scattering function.

X3.3.19 *low angular resolution, adj—in describing a BSDF measurement*, performed using angular resolution no better than 2°.

X3.3.19.1 *Discussion*—Low angular resolution measurements are appropriate for characterizing diffuse materials that do not have a significant specular reflection, or for characterizing scattering in directions well away from the specular direction.

X3.3.20 *medium angular resolution, adj—in describing a BSDF measurement*, performed using an angular resolution no better than 0.5°.

X3.3.20.1 *Discussion*—Medium angular resolution measurements are appropriate for characterizing diffusely scattering materials that have a significant specular component, but for which the details in the specular direction are not required.

X3.3.21 *high angular resolution, adj—in describing a BSDF measurement*, performed using an angular resolution better than 0.5°.

X3.3.21.1 *Discussion*—High angular resolution measurements are appropriate for characterizing specularly reflecting materials for which the details of the near specular region are required.

X3.3.22 *very high angular resolution, adj—in describing a BSDF measurement*, performed using an angular resolution better than 0.1°.

X3.3.22.1 *Discussion*—Very high angular resolution measurements are required for characterizing specularly reflecting materials, where radiometric accuracy in the near specular region is required. Such measurements are required to assure that the limit $\Omega \rightarrow 0$ is maintained in Eq 5.

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