Designation: E2387 – 19

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 Guide 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, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.14 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

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

[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.

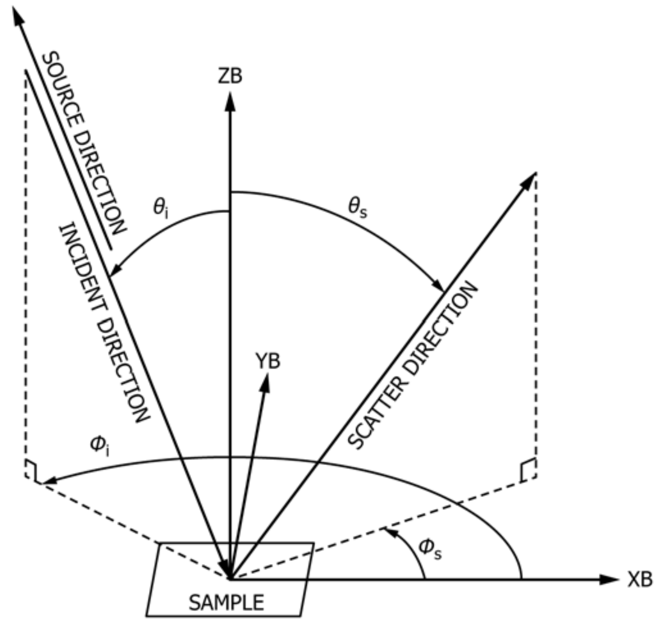


FIG. 1 Angle Conventions

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

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 Guide 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,* θ_i, *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:

$$\alpha = \theta_i - \theta_s \quad (1)$$

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

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

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:

$$\sin\theta_s\cos(\varphi_s - \varphi_i) > \sin\theta_i \quad (3)$$

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:

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

3.2.6.1 *Discussion*—BSDF is a differential function dependent on the wavelength, incident direction, scatter direction,

[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.

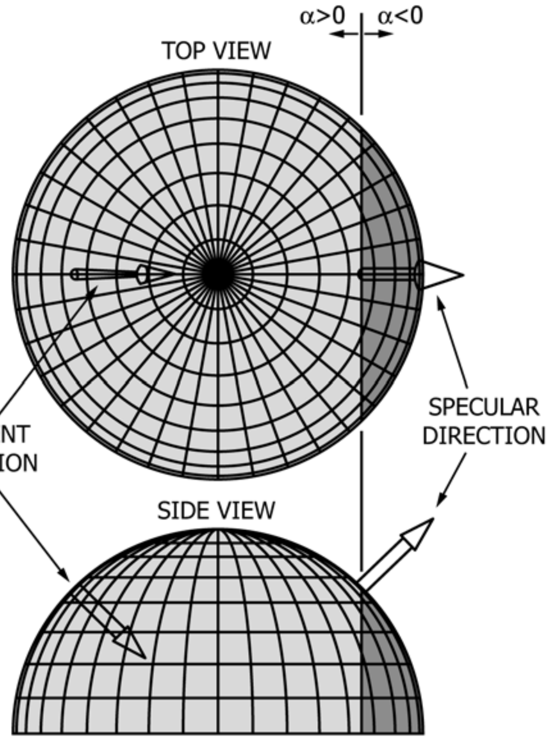


FIG. 2 Definition of the Sign of the Aspecular Angle

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:

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

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 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 multiparameter 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 noise equivalent 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.

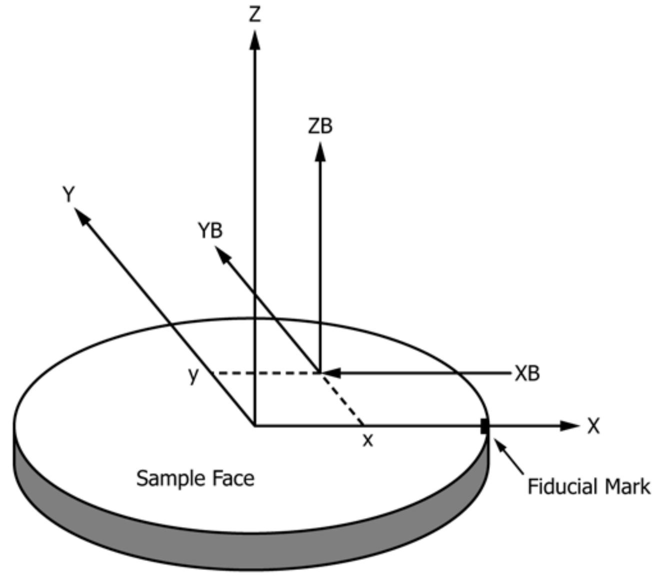
3.2.26 *sample radiance, L_e, n*—a differential quantity that is the reflected radiant flux per unit projected solid angle per unit sample area.

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, Ω cosθ_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.



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

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

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(θ)cos(φ) and sin(θ)sin(φ), 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(-θ)cos(φ+180°) = sin(θ)cos(φ) and sin(-θ)sin(φ+180°) = sin(θ)sin(φ), 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 (θ_i,φ_i; θ_s,φ_s). For example, it is common to have (θ_i; θ_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 (θ_i,φ_i; θ_s,φ_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