CHAPTER 26
SCATTEROMETERS

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26.1 GLOSSARY

<table>
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<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>BRDF</td>
<td>bidirectional reflectance distribution function</td>
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<tr>
<td>BTDF</td>
<td>bidirectional transmittance distribution function</td>
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<td>BSDF</td>
<td>bidirectional scatter distribution function</td>
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<tr>
<td>f</td>
<td>focal length</td>
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<td>FN</td>
<td>focal ratio</td>
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<td>L</td>
<td>distance</td>
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<td>P</td>
<td>power</td>
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<td>R</td>
<td>length</td>
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<td>r</td>
<td>radius</td>
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<td>TIS</td>
<td>total integrated scatter</td>
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<tr>
<td>θ</td>
<td>angle</td>
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<td>θn</td>
<td>vignetting angle</td>
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<td>θspec</td>
<td>specular angle</td>
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<td>λ</td>
<td>wavelength</td>
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<tr>
<td>σ</td>
<td>rms roughness</td>
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<td>Ω</td>
<td>solid angle</td>
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26.2 INTRODUCTION

The measurement of optical scatter has received increased attention in the last decade. In addition to being a serious source of noise, scatter reduces throughput, limits resolution, and has been the unexpected source of practical difficulties in many optical systems. On the other hand, its measurement has proved to be an extremely sensitive method of providing metrology information for components used in many diverse applications. Measured scatter is a good indicator of surface quality and can be used to characterize surface roughness as well as locate and size discrete defects. It is also used to measure the quality of optical coatings and bulk optical materials. It is emerging as a valuable noncontact measurement technique outside the optics industry as well. Point sources of
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Scatter imaged onto position-sensitive detectors are used to measure displacement. Doppler-shifted scatter is used to measure velocity, and polarization changes in scattered light can be used to reveal reflector material properties, such as the optical constants.

The instrumentation required for many of these measurements has to be fairly sophisticated. Scatter signals are generally small compared to the specular beam and can vary by several orders of magnitude in just a few degrees. Complete characterization may require measurement over a large fraction of the sphere surrounding the scatter source. For many applications, a huge array of measurement decisions (incident angle, wavelength, source and receiver polarization, scan angles, etc.) faces the experimenter. The instrument may faithfully record a signal, but is it from the sample alone? Or, does it also include light from the instrument, the wall behind the instrument, and the experimenter’s shirt? These are not easy questions to answer at nanowatt levels in the visible and get even harder in the infrared and ultraviolet. It is easy to generate scatter data—lots of it. Obtaining accurate values of appropriate measurements and communicating them requires knowledge of the instrumentation as well as insight into the problem being addressed.

In 1961, Bennett and Porteus reported measurement of signals obtained by integrating scatter over the reflective hemisphere. They defined a parameter called total integrated scatter (TIS) and, using a scalar diffraction theory result drawn from the radar literature, related it to reflector root mean square (rms) roughness. By the mid-1970s, several scatterometers had been built at various university, government, and industry labs that were capable of measuring scatter as a function of angle; however, instrument operation and data manipulation were not always well automated. Scattered power per unit solid angle (sometimes normalized by the incident power) was usually measured. Analysis of scatter data to characterize sample surface roughness was the subject of many publications. Measurement comparison between laboratories was hampered by instrument differences, sample contamination, and confusion over what parameters should be compared. A derivation of what is commonly called BRDF (for bidirectional reflectance distribution function) was published by Nicodemus and coworkers in 1970, but did not gain common acceptance as a way to quantify scatter measurements until after publication of their 1977 NBS monograph. With the advent of small powerful computers in the 1980s, instrumentation became more automated. Increased awareness of scatter problems and the sensitivity of many end-item instruments increased government funding for better instrumentation. As a result, instrumentation became available that could measure and analyze as many as 50 to 100 samples a day instead of just a handful. Scatterometers became commercially available and the number (and sophistication) of measurement facilities increased. Two ASTM standards were published (TIS in 1987 and BRDF in 1991). The 1990s will be characterized by less dramatic increases in instrumentation capabilities, but a large increase in applications. Further instrumentation improvements will include more out-of-plane capability, extended wavelength control, and polarization control at both source and receiver. These systems will find applications outside the optical industry in increasing numbers.

This review gives basic definitions, instrument configurations and components, scatter specifications, measurement techniques, and briefly discusses calibration and error analysis.

26.3 DEFINITIONS AND SPECIFICATIONS

One of the difficulties encountered in comparing measurements made on early instruments was getting participants to calculate the same quantities. There were problems of this nature as late as 1988 in a measurement round-robin run at 0.63 micrometers. But, there are other reasons for reviewing these basic definitions before discussing instrumentation. The ability to write useful scatter specifications (i.e., the ability to make use of quantified scatter information) depends just as much on understanding the defined quantity as it does...
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FIGURE 1

on understanding the instrumentation and the specific scatter problem. In addition, definitions are often given in terms of mathematical abstractions that can only be approximated in the lab. This is the case for BRDF.

\[
\text{BRDF} = \frac{dP_s}{d\Omega} = \frac{P_s/\Omega}{P_i} \cos \theta_s
\]  

BRDF has been strictly defined as the ratio of the sample differential radiance to the differential irradiance under the assumptions of a collimated beam with uniform cross section incident on an isotropic surface reflector (no bulk scatter allowed). Under these conditions, the third quantity in Eq. (1) is found, where power \( P \) in watts instead of intensity \( I \) in watts/m\(^2\) has been used. The geometry is shown in Fig. 1. The value \( \theta_s \) is the polar angle in the scatter direction measured from reflector normal and \( \Omega \) is the differential solid angle (in steradians) through which \( dP_s \) (watts) scatters when \( P_i \) (watts) is incident on the reflector. The cosine comes from the definition of radiance and may be viewed as a correction from the actual size of the scatter source to the apparent size (or projected area) as the viewer rotates away from surface normal.

The details of the derivation do not impact scatter instrumentation, but the initial assumptions and the form of the result do. When light power is measured, it is through a finite diameter aperture, and the resulting calculation is for an average BRDF over the aperture. This is expressed in the final term of Eq. (1) where \( P_s \) is the measured power through the finite solid angle \( \Omega \) defined by the receiver aperture and the distance to the scatter source. Thus, when the receiver aperture is swept through the scatter field to obtain angle dependence, the measured quantity is actually the convolution of the aperture over the differential BRDF. This does not cause serious distortion unless the scatter field has abrupt intensity changes, as it does near specular or near diffraction peaks associated with periodic surface structure. But there are even more serious problems between the strict definition of BRDF (as derived by Nicodemus) and practical measurements. There are no such things as uniform cross-section beams and isotropic samples that scatter only from
surface structure. So, the third term of Eq. (1) is not exactly the differential radiance/irradiance ratio for the situations we create in the lab with our instruments. However, it makes perfect sense to measure normalized scattered power density as a function of direction [as defined in the fourth term of Eq. (1)] even though it cannot be exactly expressed in convenient radiometric terms.

A slightly less cumbersome definition (in terms of writing scatter specifications) is realized if the cosine term is dropped. This is referred to as “the cosine-corrected BRDF,” or sometimes, “the scatter function.” Its use has caused some of the confusion surrounding measurement differences found in scatter round robins. In accordance with the original definition, accepted practice, and the ASTM Standard, the BRDF contains the cosine, as given in Eq. (1), and the cosine-corrected BRDF does not. It also makes sense to extend the definition to volume scatter sources and even make measurements on the transmissive side of the sample. The term BTDF (for bidirectional transmission distribution function) is used for transmissive scatter, and BSDF (bidirectional scatter distribution function) is all-inclusive.

The BSDF has units of inverse steradians and, unlike reflectance and transmission, can take on very large values as well as very small values. For near-normal incidence, a measurement made at the specular beam results in a BSDF value of approximately 1/Ω, which is generally a large number. Measured values at the specular direction on the order of 10^9 sr^-1 are common for a HeNe laser source. For low-scatter measurements, large apertures are generally used and values fall to the noise equivalent BSDF (or NEBSDF). This level depends on incident power and polar angle (position) as well as aperture size and detector noise, and typically vary from 10^-4 sr^-1 to 10^-10 sr^-1. Thus, the measured BSDF can easily vary by over a dozen orders of magnitude in a given angle scan. This large variation results in challenges in instrumentation design as well as data storage, analysis, and presentation, and is another reason for problems with comparison measurements.

Instrument signature is the measured background scatter signal caused by the instrument and not the sample. It is caused by a combination of scatter created within the instrument and by the NEBSDF. Any instrument scatter that reaches the receiver field of view (FOV) will contribute to it. Common causes are scatter from source optics and the system beam dump. It is typically measured without a sample in place; however, careful attention has to be paid to the receiver FOV to ascertain that this is representative of the sample measurement situation. It is calculated as though the signal came from the sample (i.e., the receiver/sample solid angle is used) so that it can be compared to the measured sample BSDF. Near specular, it is dominated by scatter (or diffraction) contributions from the source. At high scatter angles it can generally be limited to NEBSDF levels. Sample measurements are always a combination of desired signal and instrument signature. Reduction of signature, especially near specular, is a prime consideration in instrument design and use.

BSDF specifications always require inclusion of incident angle, source wavelength, and polarization as well as observation angles, scatter levels, and sample orientation. Depending on the sample and the measurement, they may also require aperture information to account for convolution effects. Specifications for scatter instrumentation should include instrument signature limits and the required NEBSDF. Specifications for the NEBSDF must include the polar angle, the solid angle, and the incident power to be meaningful.

TIS measurements are made by integrating the BSDF over a portion of the sphere surrounding the scatter source. This is usually done with instrumentation that gathers (integrates) the scattered light signal. The TIS can sometimes be calculated from BSDF data. If an isotropic sample is illuminated at near-normal incidence with circularly polarized light, data from a single measurement scan is enough to calculate a reasonably accurate TIS value for an entire hemisphere of scatter. The term “total integrated scatter” is a slight misnomer in that the integration is never actually “total”, as some scatter is not measured. Integration is commonly performed from a few degrees from specular to polar
angles approaching 90° (less than 2.5° to more than 70° in the ASTM Standard). Measurements can be made of either transmissive or reflective scatter. TIS is calculated by ratioing the integrated scatter to the reflected (or transmitted) specular power as shown below. The conversion to rms roughness ($\sigma$) under the assumption of a smooth, clean, reflective surface, via Davies’ scalar theory, is also given. This latter calculation does not require gaussian surface statistics (as originally assumed by Davies) or even surface isotropy, but will work for other distributions, including gratings and machined optics. There are other issues (polarization and the assumption of mostly near specular scatter) that cause some error in this conversion. Comparison of TIS-generated roughness to profile generated values is made difficult by a number of issues (bandwidth limits, one-dimensional profiling of a two-dimensional surface, etc.) that are beyond the scope of this section.

$$\text{TIS} = \frac{\text{integrated scatter}}{\text{reflected specular power}} = \left(\frac{4\pi\sigma^2}{\lambda}\right)$$

TIS is one of three ratios that may be formed from the incident power, the specular reflected (or transmitted) power, and the integrated scatter. The other two ratios are the diffuse reflectance (or transmittance) and the specular reflectance (or transmittance). Typically, all three ratios may be obtained from measurements taken in TIS or BSDF instruments. Calculation, or specification, of any of these quantities that involve integration of scatter, also requires that the integration limits be given, as well as the wavelength, angle of incidence, source polarization, and sample orientation.

26.4 INSTRUMENT CONFIGURATIONS AND COMPONENT DESCRIPTIONS

The scatterometer shown in Fig. 2 is representative of the most common instrument configuration in use. The source is fixed in position. The sample is rotated to the desired

![FIGURE 2 Components of a typical BSDF scatterometer.](image)
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incident angle, and the receiver is rotated about the sample in the plane of incidence. Although dozens of instruments have been built following this general design, other configurations are in use. For example, the source and receiver may be fixed and the sample rotated so that the scatter pattern moves past the receiver. This is easier mechanically than moving the receiver at the end of an arm, but complicates analysis because the incident angle and the observation angle change simultaneously. Another combination is to fix the source and sample together, at constant incident angle, and rotate this unit (about the point of illumination on the sample) so that the scatter pattern moves past a fixed receiver. This has the advantage that a long receiver/sample distance can be used without motorizing a long (heavy) receiver arm. It has the disadvantage that heavy (or multiple) sources are difficult to deal with. Other configurations, with everything fixed, have been designed that employ several receivers to merely sample the BSDF and display a curve fit of the resulting data. This is an economical solution if the BSDF is relatively uniform without isolated diffraction peaks.

Computer control of the measurement is essential to maximize versatility and minimize measurement time. The software required to control the measurement plus display and analyze the data can be expected to be a significant portion of total instrument development cost. The following paragraphs review typical design features (and issues) associated with the source, sample mount, and receiver components.

The source in Fig. 2 is formed by a laser beam that is chopped, spatially filtered, expanded, and finally brought to a focus on the receiver path. The beam is chopped to reduce both optical and electronic noise. This is accomplished through the use of lock-in detection in the electronics package which suppresses all signals except those at the chopping frequency. Low-noise, programmable gain electronics are essential to reducing NEBSDF. The reference detector is used to allow the computer to ratio out laser power fluctuations and, in some cases, to provide the necessary timing signal to the lock-in electronics. Polarizers, wave plates, and neutral density filters are also commonly placed prior to the spatial filter when required in the source optics. The spatial filter removes scatter from the laser beam and presents a point source which is imaged by the final focusing element to the detector zero position. Although a lens is shown in Fig. 2, the use of a mirror, which works over a larger range of wavelengths and generally scatters less light, is more common. For most systems the large $F$ of the final focusing element allows use of a spherical mirror with only minor aberration. Low-scatter spherical mirrors are easier to obtain than other conic sections. The incident beam is typically focused at the receiver to facilitate near specular measurement. Another option (a collimated beam at the receiver) is sometimes used and will be considered in the discussion on receivers. In either case, curved samples can be accommodated by adjusting the position of the spatial filter with respect to the final focusing optic. The spot size on the sample is obviously determined by elements of the system geometry and can be adjusted by changing the focal length of the first lens (often a microscope objective). The source region is completed by a shield that isolates stray laser light from the detector.

Lasers are convenient sources, but are not necessary. Broadband sources are often required to meet a particular application or to simulate the environment where a sample will be used. Monochromators and filters can be used to provide scatterometer sources of arbitrary wavelength. Noise floor with these tunable incoherent sources increases dramatically as the spectral bandwidth is narrowed, but they have the advantage that the scatter pattern does not contain laser speckle.

The sample mount can be very simple or very complex. In principal, six degrees of mechanical freedom are required to fully adjust the sample. Three translational degrees of freedom allow the sample area (or volume) of interest to be positioned at the detector rotation axis and illuminated by the source. Three rotational degrees of freedom allow the sample to be adjusted for angle of incidence, out-of-plane tilt, and rotation about sample normal. The order in which these stages are mounted affects the ease of use (and cost) of the sample holder. In practice, it often proves convenient to either eliminate, or
occasionally duplicate, some of these degrees of freedom. Exact requirements for these stages differ depending on whether the sample is reflective or transmissive, as well as with size and shape. In addition, some of these axes may be motorized to allow the sample area to be raster-scanned to automate sample alignment or to measure reference samples. The order in which these stages are mounted affects the ease of sample alignment. As a general rule, the scatter pattern is insensitive to small changes in incident angle but very sensitive to small angular deviations from specular. Instrumentation should be configured to allow location of the specular reflection (or transmission) very accurately.

The receiver rotation stage should be motorized and under computer control so that the input aperture may be placed at any position on the observation circle (dotted line in Fig. 2). Data scans may be initiated at any location. Systems vary as to whether data points are taken with the receiver stopped or “on the fly.” The measurement software is less complicated if the receiver is stopped. Unlike many TIS systems, the detector is always approximately normal to the incoming scatter signal. In addition to the indicated axis of rotation, some mechanical freedom is required to assure that the receiver is at the correct height and pointed (tilted) at the illuminated sample. Sensitivity, low noise, linearity, and dynamic range are the important issues in choosing a detector element and designing the receiver housing. In general, these requirements are better met with photovoltaic detectors than photoconductive detectors. Small area detectors reduce the NEBSDF.

Receiver designs vary, but changeable apertures, bandpass filters, polarizers, lenses, and field stops are often positioned in front of the detector element. Figure 3 shows two receiver configurations, one designed for use with a converging source and one with a collimated source. In Fig. 3a, the illuminated sample spot is imaged on a field stop in front of the detector. This configuration is commonly used with the source light converging on the receiver path. The field stop determines the receiver FOV. The aperture at the front of the receiver determines the solid angle over which scatter is gathered. Any light entering this aperture, that originates from within the FOV, will reach the detector and become part of the signal. This includes instrument signature contributions scattered through small

**FIGURE 3** Receiver configurations: (a) converging source; (b) collimated source.
angles by the source optics. It will also include light scattered by the receiver lens so that it appears to come from the sample. The configuration in Fig. 3a can be used to obtain near specular measurements by bringing a small receiver aperture close to the focused specular beam. With this configuration, reducing the front aperture does not limit the FOV. The receiver in Fig. 3b is in better accordance with the strict definition of BRDF in that a collimated source can be used. An aperture is located one focal length behind a collecting lens (or mirror) in front of the detector. The intent is to measure bundles of nearly parallel rays scattered from the sample. The angular spread of rays allowed to pass to the detector defines the receiver solid angle, which is equal to the aperture size divided by the focal length of the lens. This ratio (not the front aperture/sample distance) determines the solid angle of this receiver configuration. The FOV is determined by the clear aperture of the lens, which must be kept larger than the illuminated spot on the sample. The Fig. 3b design is unsuitable for near specular measurement because the relatively broad collimated specular beam will scatter from the receiver lens for several degrees from specular. It is also limited in measuring large incident angle situations where the elongated spot may exceed the FOV. If the detector (and its stop) can be moved in relation to the lens, receivers can be adjusted from one configuration to the other. Away from the specular beam, in low instrument signature regions, there is no difference in the measured BSDF values between the two systems.

The two common methods of approaching TIS measurements are shown in Fig. 4. The first one, employed by Bennett and Porteus in their early instrument, uses a hemispherical mirror (or Coblentz Sphere) to gather scattered light from the sample and image it onto a detector. The specular beam enters and leaves the hemisphere through a small circular hole. The diameter of that hole defines the near specular limit of the instrument. The reflected beam (not the incident beam) should be centered in the hole because the BSDF will be symmetrical about it. Alignment of the hemispherical mirror is critical in this approach. The second approach involves the use of an integrating sphere. A section of the sphere is viewed by a recessed detector. If the detector FOV is limited to a section of the sphere that is not directly illuminated by scatter from the sample, then the signal will be proportional to total scatter from the sample. Again, the reflected beam should be centered on the exit hole. The Coblentz Sphere method presents more signal to the

![FIGURE 4a](image1.png) TIS measurement with a Coblentz Sphere.

![FIGURE 4b](image2.png) TIS measurement with a diffuse integrating sphere.
detector; however, some of this signal is incident on the detector at very high angles. Thus, this approach tends to discriminate against high-angle scatter (which is not a problem for many samples). The integrating sphere is easier to align, but has a lower signal-to-noise ratio (less signal on the detector) and is more difficult to build in the IR where uniform diffuse surfaces are harder to obtain. A common mistake with TIS measurements is to assume that for near-normal incidence, the orientation between source polarization and sample orientation is not an issue. TIS measurements made with a linearly polarized source on a grating at different orientations will quickly demonstrate this dependence.

TIS measurements can be made over very near specular ranges by utilizing a diffusely reflecting plate with a small hole in it. A converging beam is reflected off the sample and through the hole. Scatter is diffusely reflected from the plate to a receiver designed to uniformly view the plate. The reflected power is measured by moving the plate so the specular beam misses the hole. Measurements starting closer than $0.1^\circ$ from specular can be made in this manner, and it is an excellent way to check incoming optics or freshly coated optics for low scatter.

### 26.5 Instrumentation Issues

Measurement of near specular scatter is often one of the hardest requirements to meet when designing an instrument and has been addressed in several publications.\textsuperscript{23–25} The measured BSDF may be divided into two regions relative to the specular beam, as shown in Fig. 5. Outside the angle $\theta_s$ from specular, is a low-signature region where the source optics are not in the receiver FOV. Inside $\theta_n$, at least some of the source optics scatter directly into the receiver and the signature increases rapidly until the receiver aperture reaches the edge of the specular beam. As the aperture moves closer to specular center, the measurement is dominated by the aperture convolution of the specular beam, and there is no opportunity to measure scatter. The value $\theta_n$ is easily calculated (via a small

![FIGURE 5](image-url)  
**FIGURE 5** Near specular geometry and instrument signature.
angle approximation) using the instrument geometry and parameters identified in Fig. 5, where the receiver is shown at the \( \theta_N \) position. The parameter \( F \) is the focal length of the sample.

\[
\theta_N = \frac{(r_{\text{MIR}} + r_{\text{FOV}})}{L} + \frac{(r_{\text{FOV}} + r_{\text{apt}})}{R - r_{\text{spot}}} \quad (3)
\]

It is easy to achieve values of \( \theta_N \) below 10\(^8\) and values as small as 1\(^8\) can be realized with careful design. The offset angle from specular, \( \theta_{\text{spec}} \), at which the measurement is dominated by the specular beam, can be reduced to less than a tenth of a degree at visible wavelengths and is given by

\[
\theta_{\text{spec}} = \frac{r_{\text{diff}} + r_{\text{apt}}}{R} \approx \frac{3\lambda}{D} + \frac{r_{\text{apt}}}{R} \quad (4)
\]

Here, \( r_{\text{diff}} \) and \( r_{\text{apt}} \) are the radius of the focused spot and the receiver aperture, respectively (see Fig. 5 again). The value of \( r_{\text{diff}} \) can be estimated in terms of the diameter \( D \) of the focusing optic and its distance to the focused spot, \( R + L \) (estimated as 2.5\( R \)). The diffraction limit has been doubled in this estimate to allow for aberrations.

To take near specular measurements, both angles and the instrument signature need to be reduced. The natural reaction is to “increase \( R \) to increase angular resolution.” Although a lot of money has been spent doing this, it is an unnecessarily expensive approach. Angular resolution is achieved by reducing \( r_{\text{apt}} \) and by taking small steps. The radius \( r_{\text{apt}} \) can be made almost arbitrarily small so the economical way to reduce the \( r_{\text{apt}}/R \) terms is by minimizing \( r_{\text{apt}} \)—not by increasing \( R \). A little thought about \( r_{\text{FOV}} \) and \( r_{\text{diff}} \) reveals that they are both proportional to \( R \), so nothing is gained in the near specular game by purchasing large-radius rotary stages.

The reason for building a large-radius scatterometer is to accommodate a large FOV. This is often driven by the need to take measurements at large incident angles, which creates a large spot on the sample. When viewing normal to the sample, the FOV requirements can be stringent. Because the maximum FOV is proportional to detector diameter (and limited at some point by minimum receiver lens \( FN \)), increasing \( R \) is the only open-ended design parameter available. It should be sized to accommodate the smallest detector likely to be used in the system. This will probably be in the mid-IR where, as of this writing, uniform high-detectivity photovoltaic detectors larger than 2 mm are difficult to obtain. On the other hand, a larger detector diameter means increased electronic noise and a larger NEBSDF.

Scatter sources of instrument signature can be reduced by these techniques.

1. Use the lowest-scatter focusing element in the source that you can afford and learn how to keep it clean. This will probably be a spherical mirror.
2. Keep the source area as “black” as possible. This especially includes the sample side of the spatial filter pinhole which is conjugate with the receiver aperture. Use a black pinhole.
3. Employ a specular beam dump that rides with your receiver and additional beam dumps to capture sample reflected and transmitted beams when the receiver has left the near specular area. Use your instrument to measure the effectiveness of your beam dumps.\(^{26}\)
4. Near specular scatter caused by dust in the air can be significantly reduced through the use of a filtered air supply over the specular beam path.

Away from specular, reduction of NEBSDF is the major factor in measuring low-scatter samples and increasing instrument quality. Measurement of visible scatter from a clean semiconductor wafer will take many instruments right down to instrument signature levels. Measurement of cross-polarized scatter requires a low NEBSDF for even high-scatter optics. For a given receiver solid angle, incident power, and scatter direction, the NEBSDF is limited by the noise equivalent power of the receiver (and associated electronics), once
optical noise contributions are eliminated. The electronic contributions to NEBSDF are easily measured by simply covering the receiver aperture during a measurement. Because the resulting signal varies in a random manner, NEBSDF should be expressed as an rms value (roughly equal to one-third of the peak level). An absolute minimum measurable scatter signal (in watts) can be found from the product of three terms: the required signal-to-noise ratio, the system noise equivalent power (or NEP given in watts per square root hertz), and the square root of the noise bandwidth (BW). The system NEP is often larger than the detector NEP and cannot be reduced below it. The detector NEP is a function of wavelength and increases with detector diameter. Typical detector NEP values (2-mm diameter) and wavelength ranges are shown as follows for several common detectors in Table 1. Notice that NEP tends to increase with wavelength. The noise bandwidth varies as the reciprocal of the sum of the system electronics time constant and the measurement integration time. Values of 0.1 to 10 Hz are commonly achieved. In addition to system NEP, the NEBSDF may be increased by contributions from stray source light, room lights, and noise in the reference signal. Table 1 also shows achievable rms NEBSDF values that can be realized at unity cosine, a receiver solid angle of 0.003 sr, one-second integration, and the indicated incident powers. This column can be used as a rule of thumb in system design or to evaluate existing equipment. Simply adjust by the appropriate incident power, solid angle, etc., to make the comparison. Adjusted values substantially higher than these indicate there is room for system improvement (don’t worry about differences as small as a factor of two). Further reduction of the instrument signature under these geometry and power conditions will require dramatically increased integration time (because of the square root dependence on noise bandwidth) and special attention to electronic dc offsets. Because the NEP tends to increase with wavelength, higher powers are needed in the mid-IR to reach the same NEBSDFs that can be realized in the visible. Because scatter from many sources tends to decrease at longer wavelengths, a knowledge of the instrument NEBSDF is especially critical in the mid-IR.

As a final configuration comment, the software package (both measurement and analysis) is crucial for an instrument that is going to be used for any length of time. Poor software will quickly cost work-years of effort due to errors, increased measurement and analysis time, and lost business. Expect to expend one to two work-years with experienced programmers writing a good package—it is worth it.

### 26.6 Measurement Issues

Sample measurement should be preceded (and sometimes followed) by a measurement of the instrument signature. This is generally accomplished by removing the sample and measuring the apparent BSDF from the sample as a transmissive scan. This is not an exact
measure of instrument noise during sample measurement, but if the resulting BSDF is multiplied by sample reflectance (or transmission) before comparison to sample data, it can define some hard limits over which the sample data cannot be trusted. The signature should also be compared to the NEBSDF value obtained with the receiver aperture blocked. Obtaining the instrument signature also presents an opportunity to measure the incident power, which is required for calculation of the BSDF. The ability to see the data displayed as it is taken is an extremely helpful feature when it comes to reducing instrument signature and eliminating measurement setup errors.

Angle scans, which have dominated the preceding discussion, are an obvious way to take measurements. BSDF is also a function of position on the sample, source wavelength, and source polarization, and scans can also be taken at fixed angle (receiver position) as a function of these variables. Obviously, a huge amount of data is required to completely characterize scatter from a sample.

Raster scans are taken to measure sample uniformity or locate (map) discrete defects. A common method is to fix the receiver position and move the sample in its own x-y plane recording the BSDF at each location. Faster approaches involve using multiple detectors (array cameras for example) with large area illumination, and scanning the source over the sample. Results can be presented using color maps or 3-D isometric plots. Results can be further analyzed via histograms and various image-processing techniques.

There are three obvious choices for making wavelength scans. Filters (variable or discrete) can be employed at the source or receiver. A monochromator can be used as a source. Finally, there is some advantage to using a Fourier transforming infrared spectrometer (FTIR) as a source in the mid-IR. Details of these techniques are beyond the scope of this discussion; however, a couple of generalities will be mentioned. Even though these measurements often involve relatively large bandwidths at a given wavelength (compared to a laser), the NEBSDF is often larger by a few orders because of the smaller incident power. Further, because the bandwidths change differently between the various source types given above, meaningful measurement comparisons between instruments are often difficult to make.

Polarization scans are often limited to SS, SP, PS, and PP (source/receiver) combinations. However, complete polarization-dependence of the sample requires the measurement of the sample Mueller matrix. This is found by creating a set of Stokes vectors at the source and measuring the resulting Stokes vector in the desired scatter direction. This is an area of instrumentation development that is the subject of increasing attention.

Speckle effects in the BSDF from a laser source can be eliminated in several ways. If a large receiver solid angle is used (generally several hundred speckles in size) there is not a problem. The sample can be rotated about its normal so that speckle is time averaged out of the measurement. This is still a problem when measuring very near the specular beam because sample rotation unavoidably moves the beam slightly during the measurement. In this case, the sample can be measured several times at slightly different orientations and the results averaged to form one speckle-free BSDF.

Scatter measurement in the retrodirection (back into the incident beam) has been of increasing interest in recent years and represents an interesting measurement challenge. Measurement requires the insertion of a beam splitter in the source. This also scatters light and, because it is closer to the receiver than the sample, dramatically raises the NEBSDF. Diffuse samples can be measured this way, but not much else. A clever (high tech) Doppler-shift technique, employing a moving sample, has been reported that allows separation of beam-splitter scatter from sample scatter and allows measurement of mirror scatter. A more economical (low tech) approach simply involves moving the source chopper to a location between the receiver and the sample. Beam-splitter scatter is now dc and goes unnoticed by the ac-sensitive receiver. Noise floor is now limited by scatter from the chopper which must be made from a low-scatter, specular, absorbing material. Noise floors as low as $3 \times 10^{-8} \text{sr}^{-1}$ have been achieved.
Regardless of the type of BSDF measurement, the degree of confidence in the results is determined by instrument calibration, as well as by attention to the measurement limitations previously discussed. Scatter measurements have often been received with considerable skepticism. In part, this has been due to misunderstanding of the definition of BSDF and confusion about various measurement subtleties, such as instrument signature or aperture convolution. However, quite often the measurements have been wrong and the skepticism is justified.

Instrument calibration is often confused with the measurement of $P_i$, which is why these topics are covered in the same section. To understand the source of this confusion, it is necessary to first consider the various quantities that need to be measured to calculate the BSDF. From Eq. (1), they are $P_r$, $\theta_s$, $\Omega$, and $P_i$. The first two require measurement over a wide range of values. In particular, $P_r$, which may vary over many orders of magnitude, is a problem. In fact, linearity of the receiver to obtain a correct value of $P_r$ is a key calibration issue. Notice that an absolute measurement of $P_r$ is not required, as long as the $P_r/P_i$ ratio is correctly evaluated. $P_i$ and $\Omega$ generally take on only one (or just a few) discrete values during a data scan. The value of $\Omega$ is determined by system geometry. The value of $P_i$ is generally measured in one of two convenient ways.\(^{11,19}\)

The first technique, sometimes referred to as the absolute method, makes use of the scatter detector (and sometimes a neutral density filter) to directly measure the power incident upon the sample. This method relies on receiver linearity (as does the overall calibration of BSDF) and on filter accuracy when one is used. The second technique, sometimes referred to as the reference method, makes use of a known BSDF reference sample (usually a diffuse reflector and unfortunately often referred to as the “calibration sample”) to obtain the value of $P_i$. Scatter from the reference sample is measured and the result used to infer the value of $P_i$ via Eq. (1). The $P_i \Omega$ product may be evaluated this way.

This method depends on knowing the absolute BSDF of the reference. Both techniques become more difficult in the mid-IR, where “known” neutral density filters and “known” reference samples are difficult to obtain. Reference sample uniformity in the mid-IR is often the critical issue and care must be exercised. Variations at 10.6 micrometers as large as 7:1 have been observed across the face of a diffuse gold reference “of known BRDF.”

The choice of measurement methods is usually determined by whether it is more convenient to measure the BSDF of a reference or the total power $P_i$. Both are equally valid methods of obtaining $P_i$. However, neither method constitutes a system calibration, because calibration issues such as an error analysis and a linearity check over a wide range of scatter values are not addressed over the full range of BSDF angles and powers when $P_i$ is measured (or calculated). The use of a reference sample is an excellent system check regardless of how $P_i$ is obtained.

System linearity is a key part of system calibration. In order to measure linearity, the receiver transfer characteristic, signal out as a function of light in, must be found. This may be done through the use of a known set of neutral density filters or through the use of a comparison technique\(^{34}\) that makes use of two data scans—without and with a single filter. However, there are other calibration problems than just linearity. The following paragraph outlines an error analysis for BSDF systems.

Because the calculation of BSDF is very straightforward, the sources of error can be examined through a simple analysis\(^{11,35}\) under the assumption that the four defining parameters are independent.

$$\Delta_{\text{BSDF}} = \left[ \left( \frac{\Delta P}{P} \right)^2 + \left( \frac{\Delta P}{P} \right)^2 + \left( \frac{\Delta \Omega}{\Omega} \right)^2 + \left( \frac{\Delta \theta_s \sin \theta_s}{\cos^2 \theta_s} \right)^2 \right]^{1/2} \tag{5}$$

In similar fashion, each of these terms may be broken into the components that cause
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errors in it. When this is done, the total error may be found as a function of angle. Two high-error regions are identified. The first is the near specular region (inside one degree), where errors are dominated by the accuracy to which the receiver aperture can be located in the cross-section direction. Or, in other words, did the receiver scan exactly through the specular beam, or did it just miss it? The second relatively high error region is near the sample plane where \( \cos \theta \) approaches zero. In this region, a small error in angular position results in a large error in calculated BSDF. These errors are often seen in BSDF data as an abrupt increase in calculated BSDF in the grazing scatter direction, the result of division by a very small cosine into the signal gathered by a finite receiver aperture (and/or a dc offset voltage in the detector electronics). This is another example where use of the cosine-corrected BSDF makes more sense.

Accuracy is system-dependent; however, at signal levels well above the NEBSDF, uncertainties less than \( \pm 10 \) percent can be obtained away from the near specular and grazing directions. With expensive electronics and careful error analysis, these inaccuracies can be reduced to the \( \pm 1 \) percent level.

Full calibration is not required on a daily basis. Sudden changes in instrument signature are an indication of possible calibration problems. Measurement of a reference sample that varies over several orders of magnitude is a good system check. It is prudent to take such a reference scan with data sets in case the validity of the data is questioned at a later time. A diffuse sample, with nearly constant BRDF, is a good reference choice for the measurement of \( P_i \) but a poor one for checking system calibration.

26.8 SUMMARY

The art of scatter measurement has evolved to an established form of metrology within the optics industry. Because scatter measurements tend to be a little more complicated than many other optical metrology procedures, a number of key issues must be addressed to obtain useful information. System specifications and measurements need to be given in terms of accepted, well-defined (and understood) quantities (BSDF, TIS, etc.). All parameters associated with a measurement specification need to be given (such as angle limits, receiver solid angles, noise floors, wavelength, etc.). Measurement of near specular scatter and/or low BSDF values are particularly difficult and require careful attention to instrument signature values; however, if the ASTM procedures are followed, the result will be repeatable, accurate data.

TIS and BSDF are widely accepted throughout the industry and their measurement is defined by ASTM standards. Scatter measurements are used routinely as a quality check on optical components. BSDF specifications are now often used (as they should be) in place of scratch/dig or rms roughness, when scatter is the issue. Conversion of surface scatter data to other useful formats, such as surface roughness statistics, is commonplace. The sophistication of the instrumentation (and analysis) applied to these problems is still increasing. Out-of-plane measurements and polarization-sensitive measurements are two areas that are experiencing rapid advances. Measurement of scatter outside the optics community is also increasing. Although the motivation for scatter measurement differs in industrial situations, the basic measurement and instrumentation issues encountered are essentially the ones described here.

26.9 REFERENCES

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