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Bidirectional Reflectance Measurement of Black Absorber Layers for Use in Optical Instrument Design

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ABSTRACT

The bidirectional reflectance distribution function (BRDF) plays a fundamental role in the optical characterization of a surface. The BRDF is a measure of the amount of light incident from one direction which is scattered by a surface in another direction. Integrating the BRDF over specified incidence and reflected solid angles defines the bi-hemispherical reflectance, which can be related to the absorptance and emissivity of a surface. We have designed and fabricated a high-accuracy bidirectional reflectometer and used it to measure the bidirectional reflectance of a smooth silicon substrate coated with the black absorber Aeroglaze Z302®. Two different coating thicknesses displaying different degrees of surface roughness were studied. A BRDF model consisting of diffuse, glossy, and specular components was then fitted to the experimental results. Finally, the Monte Carlo ray-trace (MCRT) method was used to split an incident beam into a group of reflected rays whose power and direction were determined by the BRDF model. The combined model is capable of simulating the performance of any optical instrument which has Z302 coated on its active surfaces. As a demonstration, the combined model is used to simulate the performance of the bidirectional reflectometer experiment used to obtain the original data.

Keywords: Radiation Heat Transfer, Monte Carlo Ray-Trace Method, Bidirectional Reflectometry

1. INTRODUCTION

An essential feature of optical instrument performance is its ability to minimize stray light [1-3]. For example, a well-sealed tube and properly constructed baffles are critical in the case of a telescope. In order to absorb stray light, interior surfaces and edges should be thoroughly blackened. Aeroglaze® Z302 (Lord) [4] is a durable polyurethane paint whose absorptivity typically exceeds 90 percent, depending on the wavelength and coating thickness. The material possesses unique properties that make it the coating of choice for many aerospace and optical applications where a surface must be an exceptionally efficient absorber. While the material is widely used in space applications, the performance of Z302 on the surface of an actual device such as a telescope has not been extensively documented in the literature.

The optical properties of coated materials are determined not only by well-known optical constants but also by the condition of the surface including roughness, granularity, and treatment. Published data for Z302 often involves many uncontrollable or unreported parameters. Therefore, a detailed investigation of the material intended for use in a specific application is recommended. The bidirectional reflectance distribution function (BRDF) of Z302 has been reported [5], and measurement-based models have been used to simulate the performance of optical instruments [2, 6-10]. The present work reports an investigation of Z302 coated on an ultra-flat silicon surface with different thicknesses and degrees of smoothness.

It is unlikely that a wavelength-dependent, bidirectional reflectivity model based entirely on theory could accurately represent the optical behavior of most surfaces of practical engineering interest. In cases where high accuracy is required, a successful surface optical model must be at least semi-empirical if not based entirely on

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measurements. We employ the semi-empirical method for Z302 to characterize the performance of the material coated on a flat silicon surface, and then use the model in the Monte Carlo ray-trace (MCRT) environment to simulate operation of the bidirectional reflectometer used to obtain the original data.

Propagation of stray light within an optical train, including specular and diffuse components, depends on the angular distribution of the radiation scattered from non-optical surfaces. The scattering pattern produced by these surfaces is determined by the bidirectional reflectance distribution function (BRDF). In the spherical coordinate system in Figure 1, the monochromatic BRDF, is defined [9]:

$$\mathrm{BRDF} = f_r(\lambda, \theta_i, \phi_i, \theta_r, \phi_r) = \frac{dL_r(\lambda,\theta_i,\phi_i,\theta_r,\phi_r)}{L_i(\lambda,\theta_i,\phi_i)\cos\theta_r d\omega_r}, \quad (1)$$

where dL_r is the differential reflected radiance from a plane surface ($W/m^2 \cdot sr$), L_i is the incident radiance onto the plane surface ($W/m^2 \cdot sr$), θ_i is the polar angle of the incident light, ϕ_i is the azimuthal angle of the incident light, θ_r is the polar angle of the reflected light, ϕ_r is the azimuthal angle of the reflected light, and $d\omega_r$ is the differential solid angle (sr). The BRDF is often referred to as the monochromatic bidirectional reflectivity. The BRDF is important because it includes all information needed to compute the other surface optical properties.

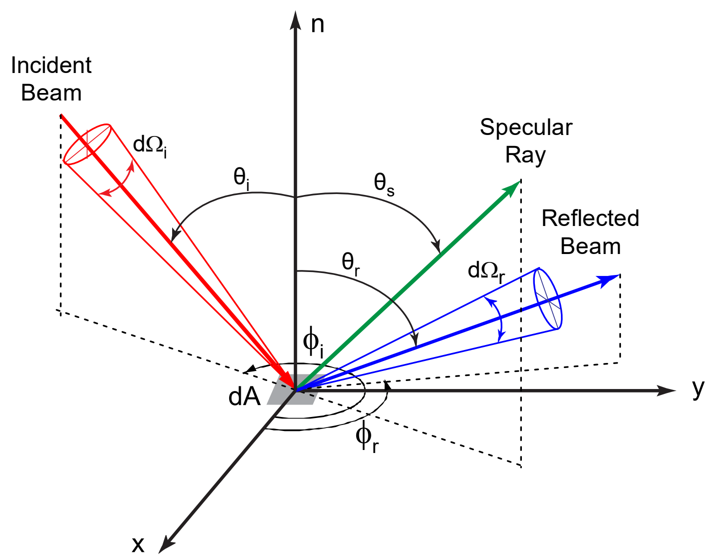

Figure 1. Beams of monochromatic light incident to and reflected from an area element dA.

2. SAMPLE FABRICATION AND EXPERIMENTAL APPARATUS

Two Z302 samples were prepared by spray-coating Z302 on 500-µm thick, polished silicon wafers. The surface of the bare silicon wafers was ultra-flat. Thus, these substrates do not produce any pattern on the surface of Z302 layers. We varied the thickness of the Z302 layers by performing a different number of re-coats to each sample. The layers were applied by hand-spraying using an air brush. Figure 2 shows two Z302 samples with coating thicknesses of 30 µm (Sample A) and 95 µm (Sample B). Sample A has a single layer with no re-coats, and Sample B has three re-coat layers. Inspection of Fig. 2 reveals that Sample A is more grainy and less shiny than Sample B.

We position the samples using the precision two-stage goniometric apparatus of our design and fabrication illustrated in Fig. 3. The goniometer achieves a coaxial rotation using two precision stage motors that are controlled using LabVIEW. These stages are assembled in a coaxial arrangement in which the first stage rotates the sample holder stick and the second stage moves the detector to the desired viewing angle position. The samples are illuminated by a power-stabilized 532-nm diode laser. The illuminating laser source is stationary, and rotation of the sample holder stick adjusts the incidence angle of the laser beam. The detector intercepts the reflected intensity by orbiting around the sample in the plane of incidence, as indicated in the figure. Adapter rings are used to assure proper alignment.

Figure 2. Two Z302 samples (A and B) used in the BRDF experiments. The thicknesses of Z302 layers for Samples A and B on an ultra-flat silicon surface are 30 and 95 µm, respectively.

Figure 4 is a schematic diagram of the entire experimental apparatus used to obtain the experimental results reported here. The polarization of the laser is controlled by a half-wave plate and a polarizing beam-splitter cube. A chopper is used to modulate the intensity of the laser beam and, in concert with a lock-in amplifier, to eliminate the effects of fluctuations in laboratory lighting. The laser beam illuminates the center of the Z302 samples. The scattered light from the surface of the Z302 samples is incident to a 200-µm slit mounted on the entrance aperture of a Newport 918-UV photodetector (for UV and visible light detection). The area of the slit determines the solid angle of our measurements.

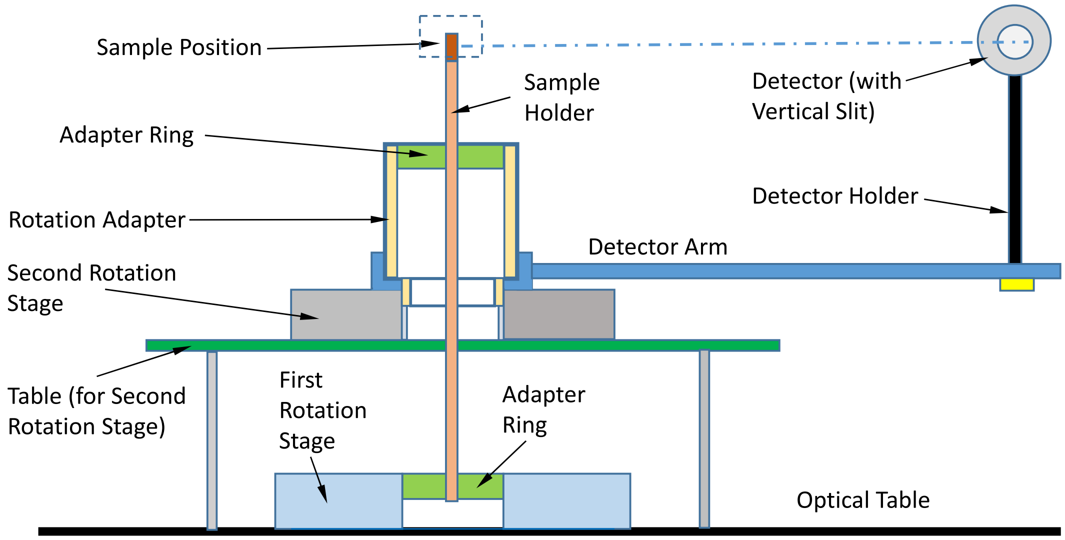

Figure 3. Schematic diagram of the bidirectional reflectometer (not to scale).

3. RESULTS AND DISCUSSION

The incident angles for BRDF measurements can be varied from 10 to 80 deg. The measured BRDFs appear in Fig. 5 for Sample A with the incident angles of 10, 30, 40, 70, and 80 deg for both *s*- and *p*- polarizations. The BRDFs for Sample B are presented in Fig. 6 for an incident angle of 80 deg for both *s*- and *p*- polarizations. To facilitate comparison, the ordinates have the same scale in both figures. The main interest of our study is to investigate the BRDFs of the black absorber (Z302) layers near the specular peaks. Therefore, data for viewing angles, θ_r, were obtained only within a limited range surrounding the direction of specular reflection. Viewing angle intervals of 0.5, 0.2, and 0.05 deg are used near the specular reflection angle, while 5-deg intervals are used for off-specular angles. To reduce random error, the reflection intensity has been averaged over three observations for each viewing angle. Near the specular peaks the standard deviation was observed to be within ±5 percent, while for very small BRDF values the standard deviation was as large as ±30 percent due to the low signal-to-noise ratio.

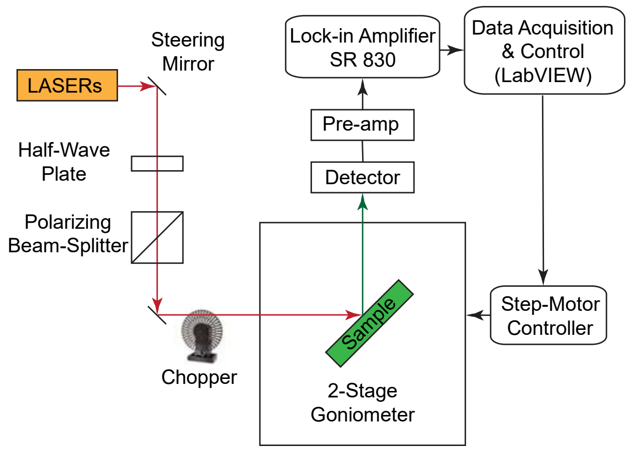

Figure 4. Schematic diagram of the experimental apparatus.

The BRDFs as well as the specular peaks at $\theta_r = \theta_i$ exhibit different magnitudes and shapes for individual samples. The measured BRDFs for Sample A decrease by about six orders of magnitude from the peak for an incident angle of 80 deg to the smallest values, while for Sample B, the peak values are more than one order of magnitude greater than those of Sample A. The shape of specular peaks in the BRDFs for these samples is different and consistent with the appearance of their surfaces shown in Fig. 2. The shape and the magnitude of the BRDFs for Sample B are comparable with previous reports of Z302 [2, 5]. However, the peaks of the BRDFs for Sample A at large reflection angles are about an order of magnitude lower than those for Sample B, suggesting that the light scattering of Sample A is more diffuse. The peak magnitudes are higher for the *s*- polarization than for the *p*- polarization for these samples. The peak intensity of BRDF measurements for the *p*- polarization decreases from the normal to about 60 deg of incident angle, and then increases by several orders of magnitude with increasing incidence angle. This is consistent with the Fresnel reflection from a smooth electrically conducting interface.

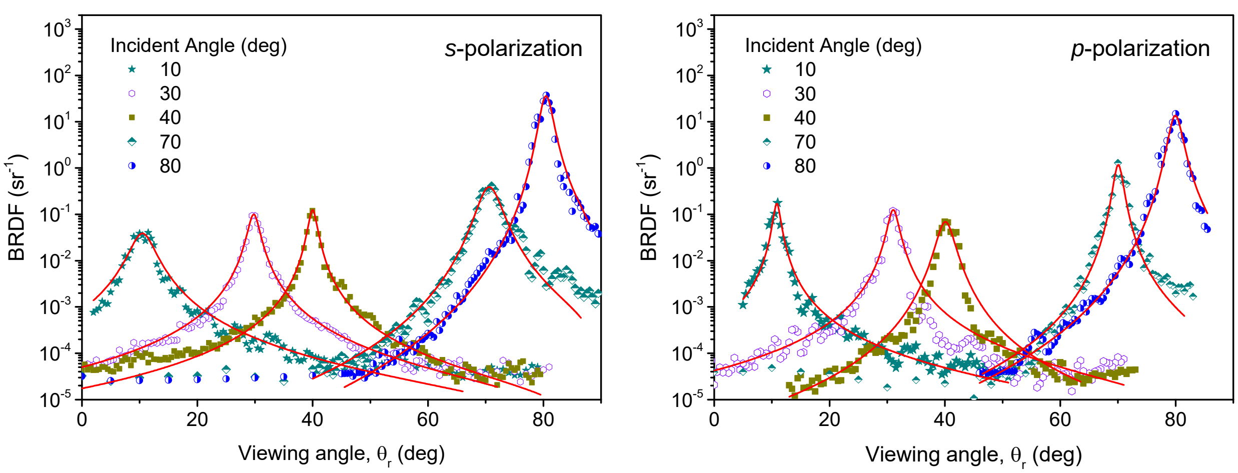

Figure 5. Measured BRDF (symbols) and a two-component BRDF model (red curves) fitted to the data obtained at 532 nm for Sample A at incident angles of 10, 30, 40, 70, 80 deg for both (left) *s*- polarization and (right) *p*- polarization.

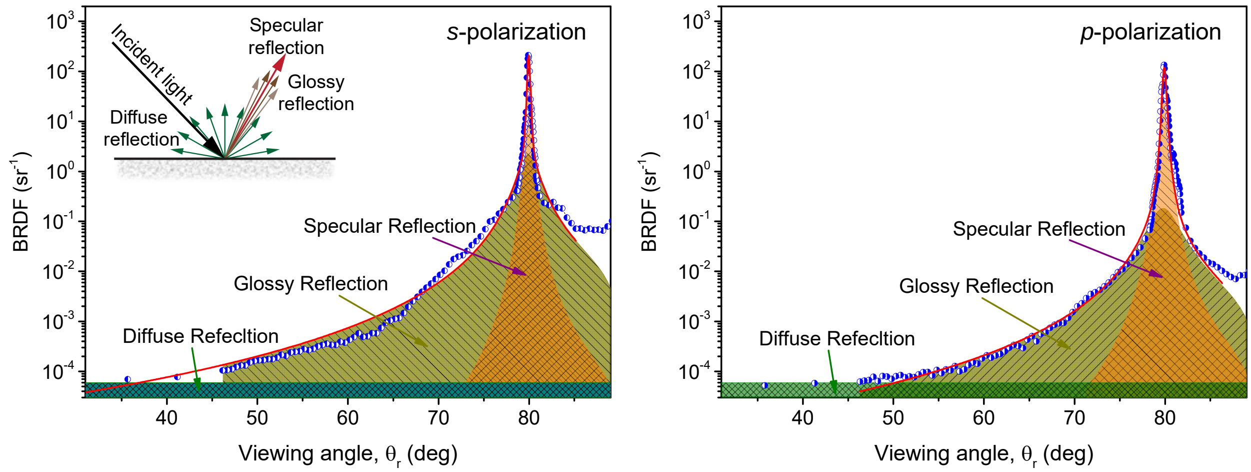

Figure 6. BRDFs measured at 532 nm for Sample B coated with Z302 at an incident angle of 80 deg for both (left) *s*- polarization and (right) *p*- polarization. The red curves are the three-component BRDF fits of the experimental results. A deconvolution for the three components is illustrated for the glossy, specular, and diffuse reflections. The three reflection components are indicated in the inset.

To accurately predict the performance of an optical instrument coated with Z302, a BRDF model is needed that accurately mimics the observed BRDF behavior of the material as a function of wavelength, incidence, and reflected (viewing) angles. The measured BRDFs for Sample A show a typical bidirectional reflection behavior and thus can be explained using scattering models. However, the measured BRDFs for Sample B contain a sharp peak and a broader base. We have used a phenomenological approach to explain the experimental results. Analysis of the available experimental data shows that the BRDF, f_r, can be represented by a linear combination of a diffuse, $f_{r,d}$, a glossy, $f_{r,g}$, and a specular, $f_{r,s}$, component [2]; i.e.,

$$f_r = k_d f_{r,d} + k_s f_{r,s} + k_g f_{r,g}, \tag{2}$$

where k_d, k_s, and k_g are nonnegative values and $k_d + k_s + k_g = 1$. The BRDF model must obey the energy conservation law, i.e., the directional-hemispherical reflectance (DHR), ρ,

$$\rho(\theta_i) = \int_{\phi_r=0}^{2\pi} \int_{\theta_r=0}^{\pi/2} f_r(\lambda, \theta_i, \phi_i, \theta_r, \phi_r) \sin\theta_r \cos\theta_r \, d\theta_r d\phi_r \tag{3}$$

must be less than unity for any incidence angle θ_i.

The diffuse component corresponds to radiation reflected uniformly within the hemispherical solid angle. The ideal diffuse reflection, known as Lambertian reflection, can be used for the diffuse reflection when $f_{r,d}$ is constant; i.e.,

$$f_{r,d} = \frac{R_d}{\pi}, \tag{4}$$

where R_d is the diffuse reflection constant.

For the glossy and specular components, the BRDF results can be explained with scattering models. An unlimited number of BRDF models are available, derived by many researchers attempting to interpret phenomena in their specific areas of interest. Our purpose is to investigate the BRDF behavior of Z302 as a function of wavelength, incidence angle, and viewing angle. The K-correlation is the most suitable approach to accomplish this. In this model, the projected vectors in scattered and specular directions are defined $\vec{\beta} = \vec{r_r} \sin\theta_r$; $\overrightarrow{\beta_0} = \overrightarrow{r_0} \sin\theta_0$, where $\vec{\beta}$ and $\overrightarrow{\beta_0}$ indicate the vectors in the scatter and specular reflection directions. The angles θ_r and θ_0 are the scatter and specular angles, respectively. These are measured relative to the surface normal. The vectors $\vec{r_r}$ and $\overrightarrow{r_0}$ are the incident and specular light rays. Thus, the K-correlation model, used to simulate the BRDFs for a smooth surface ($\hat{\sigma} \ll 1$), can be expressed as a function of $|\vec{\beta} - \overrightarrow{\beta_0}|$ [11]; i.e.,

$$BRDF_{\text{K-corr}}(s \neq 2) = \frac{2\pi\, dn^2 R B^2}{\lambda^4} \frac{\sigma^2(\lambda)(s-2)}{\left(1-(1+(B/\lambda)^2)^{1-s/2}\right)} \frac{\cos\theta_i \cos\theta_r}{(1+B^2(\beta-\beta_0)^2/\lambda^2)}$$

and (5)

$$BRDF_{\text{K-corr}}(s = 2) = \frac{4\pi\, dn^2 R B^2}{\lambda^4} \frac{\sigma^2(\lambda)}{\ln(1+(B/\lambda)^2)} \frac{\cos\theta_i \cos\theta_r}{(1+B^2(\beta-\beta_0)^2/\lambda^2)} .$$

In Eq. (5), λ is the measurement wavelength, s is the slope of BRDF at large spatial frequencies, $B = 2\pi L_c$ in which L_c is the surface correlation length, $\sigma(\lambda)$ is the total effective rms roughness over the frequency range, R is the surface specular reflectivity, and dn is the change in the refractive index at the surface ($dn = 2$ for mirror).

The measured BRDFs for Sample A can be fitted with a combination of a diffuse reflection (Lambertian reflection) and a specular reflection (K-correlation model). Figure 5 reveals excellent fitting curves of the two-component BRDF model to the experimental results. Values obtained from the two-component BRDF model provide information to predict the BRDF behavior of Z302 as a function of wavelength, incidence, and viewing angles for our MCRT simulations.

The measured BRDFs for Sample B appear to be composed of more components. The specular component is a type of surface reflectance often described as a mirror-like reflection of light from a surface. A glossy component exhibits more angular spread and so produces a specular lobe rather than a peak. We have employed three scattering models here to explain the experimental results as well as to mimic the BRDF behavior of Z302 for use to predict the performance of an optical instrument. Specifically, we have employed a combination of one component based on the Lambertian model for diffuse reflection, and two components using the K-correlation model for the specular and the glossy reflections. Figure 6 shows a deconvolution of the BRDFs into three reflection components for *s*- and *p*-polarization at the incident angle of 80 deg.

We have employed the scattering model to calculate BRDFs from Z302 layers for the incident angle of 45 deg using the MCRT method. Figure 7 illustrates the resulting three-component reflection pattern consisting of specular, glossy, and diffuse components. This result was obtained by tracing 100,000 optical rays created by splitting a single ray incident at (x, y, z) = (0, 0, 0) at an angle of 45 deg. The illuminated sample lies in the x,y-plane. The BRDF is a function of wavelength and of incidence and viewing angles. Thus, we can use our models, with experimentally determined fitting parameters, to perform simulations describing the performance of an optical instrument.

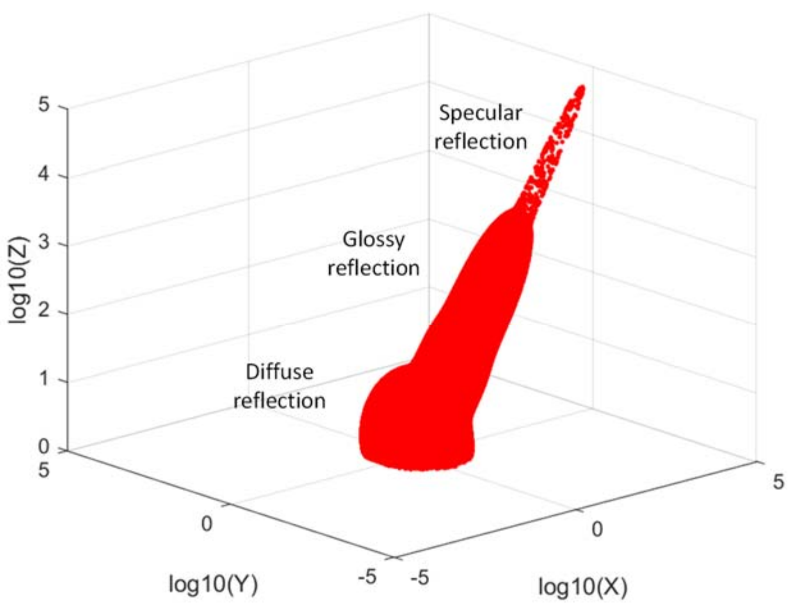

Figure 7. The BRDF predicted using our model shows multiple reflection processes including specular, glossy and diffuse components of a single optical ray incident at (x, y, z) = (0, 0, 0) at an angle of 45 deg.

4. SUMMARY AND CONCLUSIONS

We have designed and fabricated a custom bidirectional reflectometer consisting of a two-stage goniometer and various optical elements, and demonstrated its use for investigating the bidirectional reflectance of two Z302-coated samples having different thicknesses and different surface roughness. The sample in each case was illuminated by a power-stabilized diode laser, and the signal was measured by a large-dynamic-range photo-detector. The BRDFs of the Z302 layers vary in magnitude and shape with viewing angle. A BRDF model consisting of diffuse, glossy, and specular components has been adapted to explain the experimental results and to mimic scattering processes in Z302 layers. Finally, the bidirectional reflectivity model has been used in the MCRT environment to simulate collection of the original experimental data. The model is now available for use in simulating the performance of any optical instrument whose surfaces are coated with Z302.

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