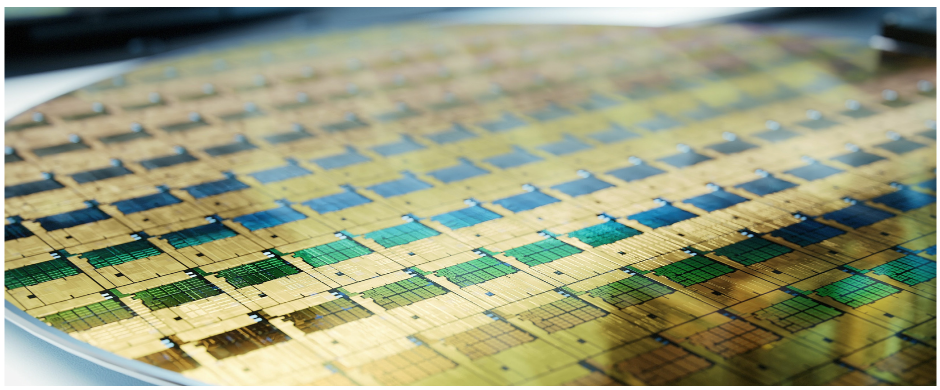
Application Note

Materials

Measurement of Bidirectional Transmittance Distribution Function

Using the Agilent Cary 7000 universal measurement spectrophotometer



Authors

Robin Aschan
Metrology Research Institute,
Aalto University,
Espoo, Finland

Travis Burt
Agilent Technologies, Inc.

Abstract

The Agilent Cary 7000 universal measurement spectrophotometer (UMS) is an effective tool for measuring the bidirectional transmittance distribution function in the visible and near-infrared ranges. It offers precise and reliable measurements with automated control over detector position, sample rotation, and polarization. Compared to a custom-built instrument, the Cary 7000 UMS is easy to configure and operate, while maintaining acceptable uncertainty levels. Its user-friendly interface makes it suitable for routine optical metrology applications, validating its use for characterizing the optical properties of materials.

Introduction

The bidirectional transmittance distribution function (BTDF) is a fundamental concept in optical metrology, describing how light is transmitted through a material in various directions. Understanding BTDF is essential for characterizing the optical properties of materials.

To address BTDF, it is important to first understand the bidirectional scattering distribution function (BSDF). BSDF encompasses both the bidirectional reflectance distribution function (BRDF) and BTDF. While BRDF measures how light is reflected off a surface, BTDF focuses on the transmission of light through a material. Together, these functions provide a comprehensive picture of how light interacts with materials, enabling precise characterization of their optical behavior.[1,3]

BTDF measurements are used in diverse fields to understand how light is transmitted through materials. In computer graphics, BTDF data enables realistic rendering of materials, enhancing visual simulations and animations with lifelike quality.[4] Remote sensing relies on BTDF to calibrate satellite sensors, improving the accuracy of earth observation data necessary for monitoring environmental changes and weather patterns.[5] Optical device design benefits from BTDF measurements by optimizing the performance of lenses, diffusers, and light-emitting devices, ensuring efficient light transmission.[4] In materials science, BTDF characterizes the optical properties of new materials, aiding in the development of advanced composites and coatings.[6] The food industry uses BTDF to assess the quality and consistency of products through their optical characteristics, which is vital for quality control.[6] The solar industry uses BTDF to enhance the efficiency of solar panels and photovoltaic devices by understanding light transmission properties.[6] Additionally, the aerospace sector uses BTDF to evaluate the optical properties of materials used in satellites and other space applications, ensuring reliable performance under various conditions.[4]

The focus of this work is to demonstrate that BTDF measurements in the visible and near-infrared (NIR) spectral range can be easily performed using the Agilent Cary 7000 universal measurement spectrophotometer (UMS), Figure 1. Alternatively, the Agilent Cary 5000 and 6000i instruments equipped with the universal measurement accessory (UMA) may also be used for BTDF measurements. These instruments offer automated control over detector position, sample rotation, and polarization, making BTDF measurements straightforward and reliable.

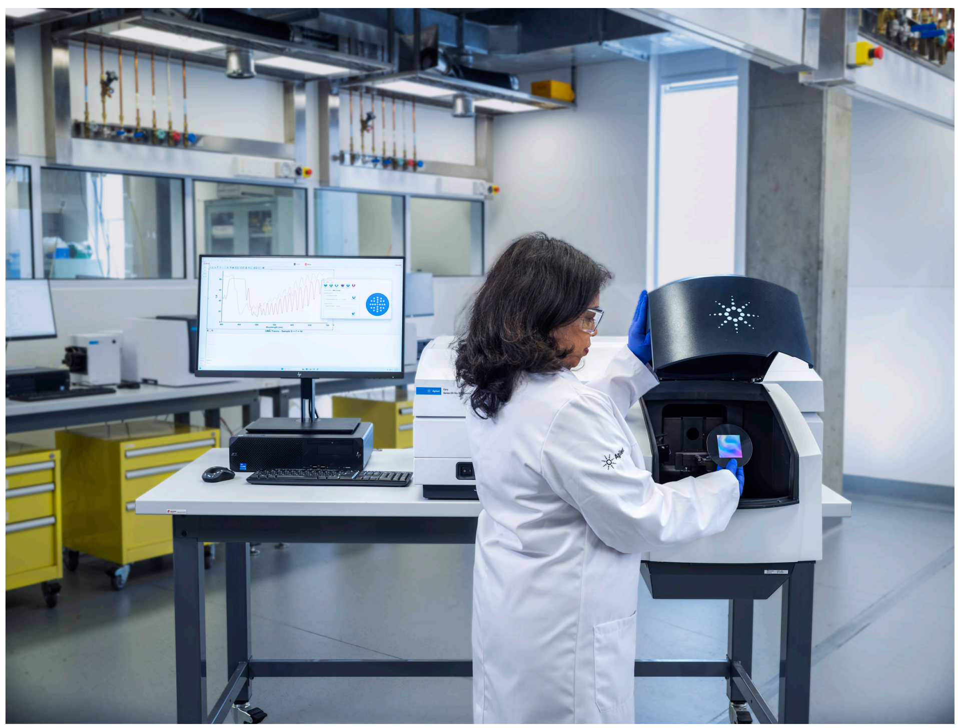


Figure 1. The Agilent Cary 7000 UMS measures absolute reflection and transmission in a single sequence—at variable angle and s or p polarization—without moving or disturbing the sample.

Experimental

Measurement schematics

The setup for measuring how light passes through a sample (BTDF) is shown in Figure 2. Spherical coordinates define the angles at which light hits and leaves the sample. The incident beam of light is characterized by its zenith and azimuth angles, which are measured relative to the surface of the sample. Similarly, the transmitted beam is defined by its own zenith and azimuth angles. The relationship (angles and geometry) between the transmitted radiance (light leaving the sample) and the incident irradiance (light hitting the sample) is used to measure the distribution of light passing through the sample, which is recorded as an electrical signal by the detector.

Figure 3 shows the setup of the Cary 7000 UMS used for measuring BTFD. The system uses a quartz tungsten-halogen lamp and a deuterium arc lamp to provide light, which is then filtered through a double monochromator (DMC) to ensure it is monochromatic. The light beam is modulated by a chopper, creating both a sample beam and a reference beam. The sample beam enters the UMA, where its polarization state, beam size, and cone angle can be controlled to form a precise illumination patch on the sample. The detection system includes turntables that set the angles at which light hits and leaves the sample. The scattered light is collected by a dual-band Si/InGaAs photodetector, which measures the light in both ultra-violet, visible and NIR ranges.

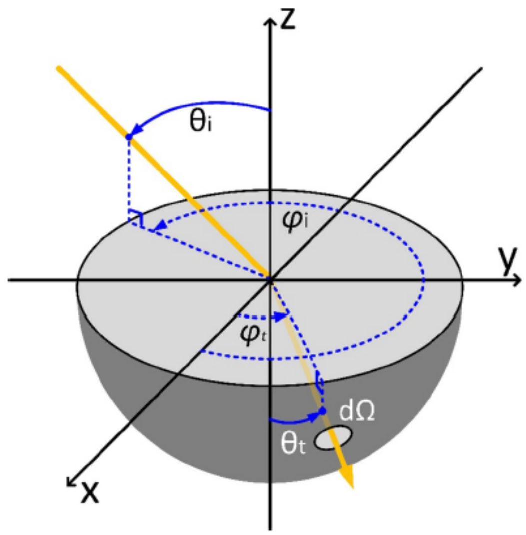


Figure 2. Bidirectional transmittance distribution function measurement geometry.

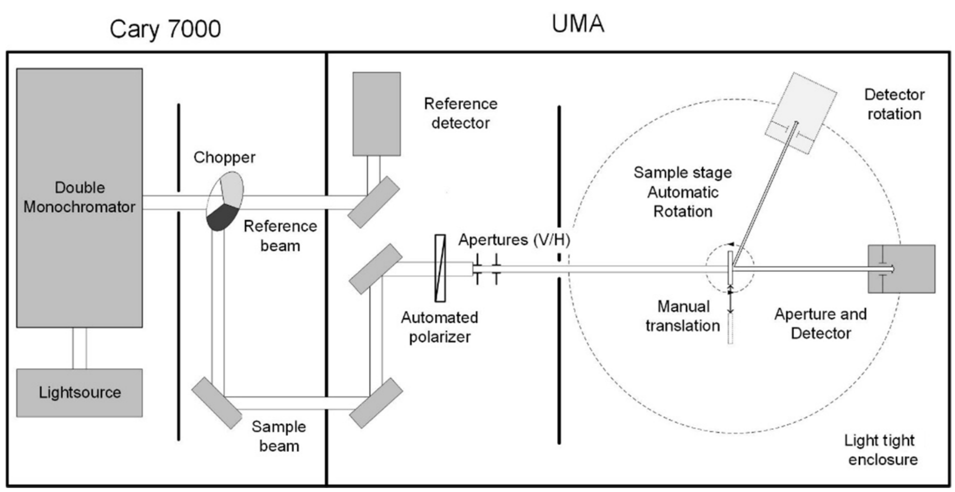


Figure 3. Schematic of the Agilent Cary 7000 universal measurement spectrophotometer setup.

Setup for the Cary 7000 UMS

The Cary 7000 UMS was used for measurements of directional and bidirectional transmittance with in-plane geometries ranging from −85° to 85° viewing angles. The instrument is easily configured using Agilent Cary WinUV software, as shown in Figures 4 and 5, and method parameters are summarized in Table 1. The source system included a quartz tungsten-halogen lamp and a deuterium arc lamp for UV illumination, coupled with a Littrow out-of-plane DMC. The DMC output slit provided a 4 nm bandwidth for the illuminating beam. The optics directed the beam onto a chopper, forming a double-beam photometric configuration. The reference beam monitored the illumination source for any drift in intensity, while the sample beam was shaped by vertical and horizontal slits to control convergence, resulting in an approximately 5.0 × 4.5 mm beam spot on the sample.

The detection system included a set of turntables regulated by an optical encoder wheel with an angular resolution of 0.02°. The sample holder and detector turntables set the incident and viewing zenith angles within ± 85°. If BRDF were to be performed, excluded angles would be between ± 10° due to shadowing by the detector. The detector setup featured a calibrated aperture with an 18.00 mm diameter and a sample-to-detector-aperture distance of 129 mm, resulting in a solid angle of 0.0153 sr. The scattered light was collected by an off-axis mirror onto a dual-band Si/InGaAs photodetector for the visible and NIR wavelength range.

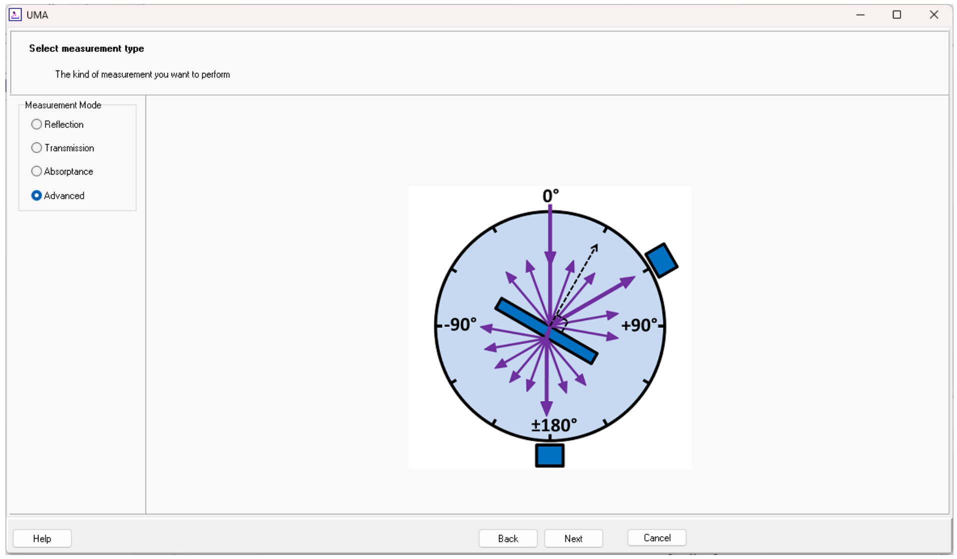


Figure 4. The Cary WinUV software features a method sequencer guides you through the setup, step by step, with clear schematics and simple selections.

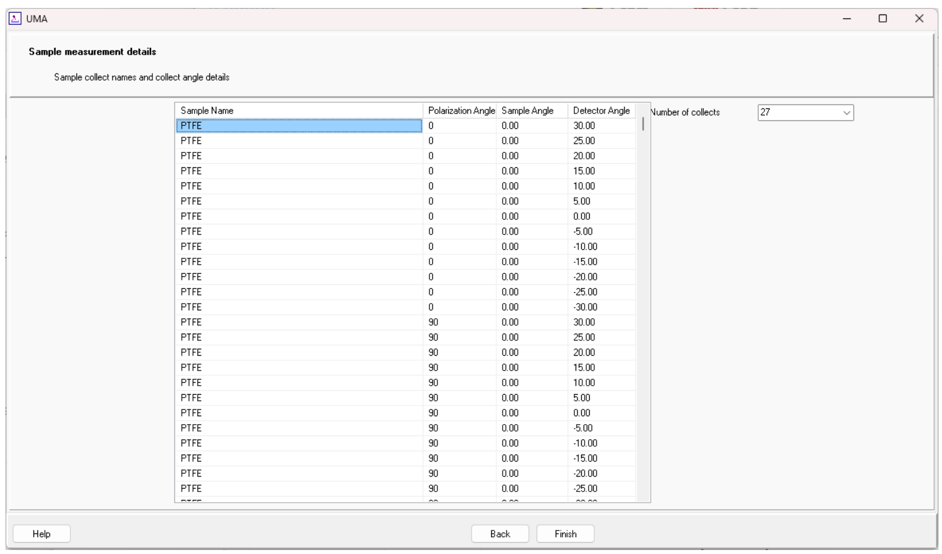


Figure 5. The intuitive interface enables precise setup of absolute reflection or transmission measurements, with independent movement and automated control of the polarizer angle, sample, and detector positioning.

Table 1. Instrument method parameters.

Parameter	Value
Sample-Detector-Aperture Distance	129 mm
Detector Aperture Diameter	18.00 mm
Beam Size	5.0 × 4.5
Bandwidth	4 nm
Detector Solid Angle	0.0153 sr
Monochromator	Double out-of-plane Littrow
Detector	Sandwich Si/InGaAs photodetector
Sources	Deuterium arc lamp, quartz-tungsten-halogen lamp

The Cary 7000 UMS used an included script to automatically set and record instrument parameters like polarization, wavelength, and viewing angles. The script also recorded electrical signals with an integration time of 2 to 9 seconds, repeating each measurement three times. Instead of using spectral radiant fluxes, the instrument used the ratio of electrical signals for sample and full signals.

BTDF measurement calculations

The BTDF for the Cary 7000 UMS measurements were calculated as:

Equation 1.

$$f = \frac{\rho}{\cos\theta\ \omega} \div 100\%$$

Where θ is the viewing zenith angle, ω is the solid angle, and ρ is the scattering ratio obtained from the Cary 7000 UMS custom script written by M. R. Fisher (2018) as:

Equation 2.

$$\rho = \frac{S - S_d}{BL - S_d} \cdot 100\%$$

Where S is the sample signal, S_d is the dark signal obtained in the beginning of the measurement, and BL is the baseline obtained in the beginning of the measurement. The solid angle was obtained from the half-angle α as:

Equation 3.

$$\omega = 2\pi \cdot (1 - 2\cos\alpha)$$

Reference materials

Two reference materials were characterized for their BTDF: porous polytetrafluoroethylene (PTFE) and fused synthetic silica (SiO_2), specifically HOD-500. The PTFE sample, provided by Schreder of CMS—ING, was cut into a rectangular sheet with dimensions of 60 × 40 × 0.5 mm. The sample was pressed flat between two pieces of black plastic filament in a custom-made frame. The HOD-500 sample, manufactured by Heraeus Quarzglas GmbH & Co., had a diameter of 50 mm and a thickness of 2 mm. It included a uniform distribution of micropores, enhancing diffuse transmission of the incident beam.

Results and discussion

Uncertainty characterization

The primary sources of uncertainty for the Cary 7000 UMS included measurement noise, instrument reproducibility, wavelength accuracy, stray light correction, detector linearity, spatial nonuniformity, sample-to-detector-aperture distance, detector aperture diameter, sample surface position, viewing zenith angle, and polarization state. The uncertainty components and their effect on relative uncertainty in BTDF measurements are listed in Table 2.

Table 2. Uncertainty components of the Agilent Cary 7000 universal measurement spectrophotometer and their effect on relative uncertainty in BTDF measurements (Si: 450 to 950 nm, InGaAs: 950 to 1,650 nm, viewing zenith angle = −35° to 35°).

Source of Uncertainty	Standard Uncertainty		Uncertainty in BTDF/%	
	Si	InGaAs	Si	InGaAs
Measurement Noise	0.09 to 0.88%	0.04 to 0.35%	0.09 to 0.88	0.04 to 0.35
Instrument Reproducibility	0.70%	0.32%	0.70	0.32
Wavelength*	0.08 nm	0.4 nm	0.01	0.02
Stray Light (Isochromatic)	0.38%	0.18%	0.38	0.18
Stray Light (Heterochromatic)	< 0.01%	< 0.01%	< 0.01	< 0.01
Detector Linearity	0.08%	0.12%	0.08	0.12
Spatial Nonuniformity*	0.14%	0.16%	0.14	0.16
Sample-to-Detector-Aperture Distance	0.6 mm	0.6 mm	0.92	0.92
Detector Aperture Diameter	2 µm	2 µm	0.02	0.02
Sample Surface Position*	0.04 mm	0.04 mm	0.06	0.06
Viewing Zenith Angle*	0.10°	0.10°	0.03	0.03
Polarization*	0.05%	0.05%	0.05	0.05
Combined Standard Uncertainty	NA	NA	1.23 to 1.51	1.07

* This uncertainty depends on the sample.

Measurement noise was mitigated by increasing the integration time from 2 to 9 seconds, resulting in relative uncertainties ranging from 0.09 to 0.88% in the visible wavelength range and from 0.04 to 0.35% in the NIR wavelength range. Instrument reproducibility was estimated by taking the standard deviations of several BTDF measurements, yielding uncertainties of 0.70% in the visible range and 0.32% in the NIR range. Wavelength accuracy was ensured by calibrating the wavelength scale against low-pressure Hg lamp lines, resulting in uncertainties of 0.01% in the visible range and 0.02% in the NIR range.

Stray light correction factors were evaluated using a method involving measurements with a sample and a mirror, resulting in reproducibility of 0.38% in the visible range and 0.18% in the NIR range. Detector linearity was assessed using a double filter method, yielding uncertainties of 0.08% in the visible range and 0.12% in the NIR range. Spatial nonuniformity was evaluated by recording BTDF values around the geometrical center of the sample, resulting in uncertainties of 0.14% in the visible range and 0.16% in the NIR range.

The sample-to-detector-aperture distance was measured using a standard tape measure ruler, resulting in uncertainties of 0.6 mm (0.92%). The detector aperture diameter was calibrated by optical methods, resulting in uncertainties of 0.02%. The sample surface position was measured using calipers, resulting in uncertainties of 0.06%. The viewing zenith angle was aligned using a mirror and the measurement beam, resulting in uncertainties of 0.03%. The polarization state was estimated from the extinction coefficient of the polarizer, resulting in uncertainties of 0.05%.

The combined standard uncertainty of the Cary 7000 UMS was 1.23 to 1.51% in the visible range and 1.07% in the NIR range, with a coverage factor of k = 2 for a confidence level of 95%.

BTDF measurement by the Cary 7000 UMS

The Cary 7000 UMS was used to measure the spectral BTDF of two samples: fused synthetic silica (HOD-500) and porous polytetrafluoroethylene (PTFE).

Measurements were conducted across the wavelength range of 450 to 1,650 nm in 50 nm intervals, and viewing zenith angles from −35° to 35° in 5° steps. Figures 6 and 7 illustrate the BTDF results for both samples.

Figure 6A shows the BTDF of the HOD-500 sample, while Figure 6B presents the BTDF of the PTFE sample. Both samples exhibited near-Lambertian characteristics and a smooth increase in BTDF as a function of wavelength.

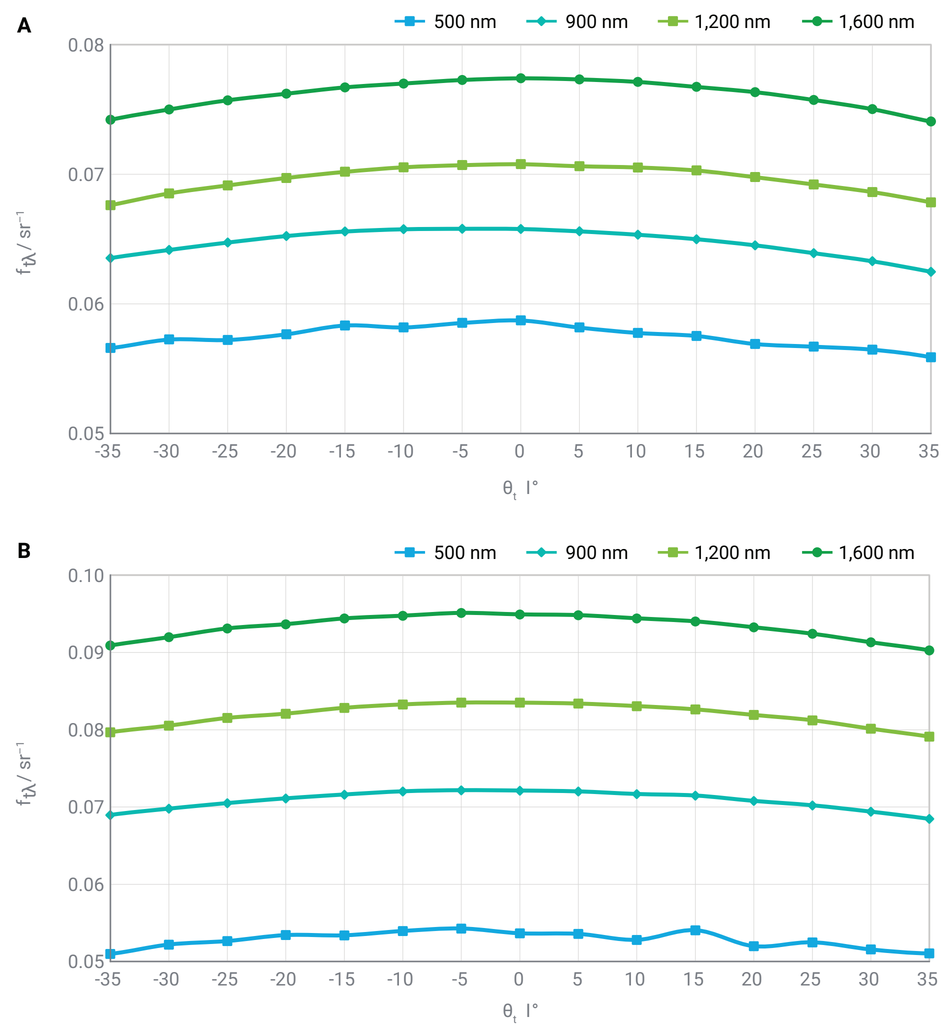


Figure 6. BTDF results for (A) the HOD-500 sample and (B) the PTFE sample at four different wavelengths.

The HOD-500 sample measured closer to Lambertian characteristics compared to the PTFE sample, with deviations of −0.22% and −0.49% from Lambertian at $\theta_t = 10°$, and −3.0% and −4.1% at $\theta_t = 35°$, respectively.

Figure 7 shows the BTDF of both samples as a function of wavelength at a viewing zenith angle of 25°. The PTFE sample exhibited a steeper increase in BTDF, particularly above 650 nm, while the HOD-500 sample showed a flatter spectral response. Below 650 nm, the HOD-500 sample measured higher BTDF values than the PTFE sample, with a relative difference of 10% at 450 nm. At longer wavelengths, the PTFE sample measured approximately 23% higher BTDF than the HOD-500 sample at 1,650 nm.

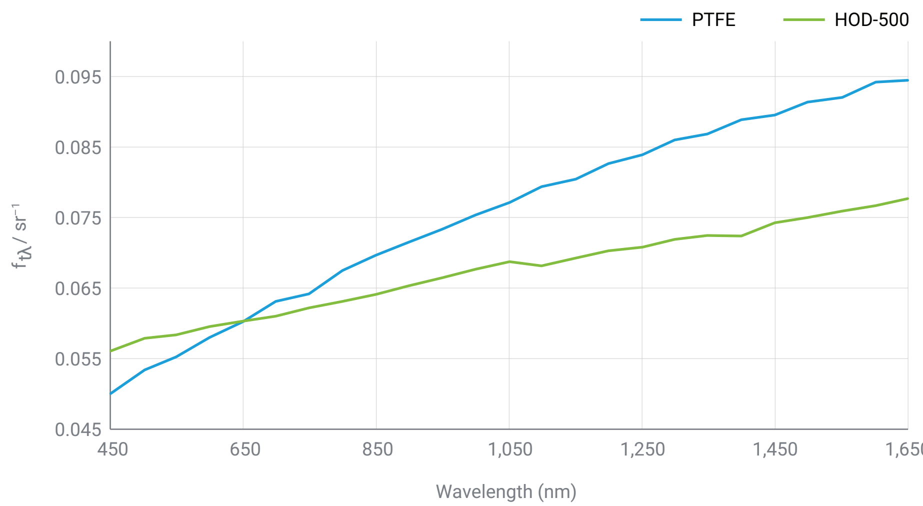


Figure 7. BTDF results of the PTFE and HOD-500 samples as a function of wavelength in the visible to NIR wavelength ranges. The BTDF is measured at a viewing zenith angle of 25°.

The Cary 7000 UMS versus a custom-built instrument for BTDF measurements

A thorough evaluation of the Cary 7000 UMS for BTDF measurements is discussed in Aschan *et al.*[7] In this work, the commercially available Cary 7000 UMS is compared against a custom-built instrument for BTDF measurements.

Results show that the Cary 7000 UMS offers a practical and efficient solution for BTDF measurements in the visible and NIR spectral ranges. Compared to the custom-built instrument, the Cary 7000 UMS is easier to configure and operate, using standard factory settings and Cary WinUV software for automated measurement processes.

While the custom-built instrument exhibits lower combined standard uncertainties (0.29 to 0.42% in the visible range and 0.40% in the NIR range), the Cary 7000 UMS maintains acceptable uncertainty levels (1.23 to 1.51% in the visible range and 1.07% in the NIR range). It should be noted, that for the Cary 7000 UMS it is possible to lower the uncertainty of the sample-to-detector-aperture distance from 0.6 to 0.1 mm (0.92 to 0.15%) by using a different measurement device or using a micrometer-based sample stage.

Both instruments demonstrated good agreement within their expanded uncertainties (95% confidence level) for BTDF measurements, validating the Cary 7000 UMS as a reliable tool. Its user-friendly interface and ease of configuration make it suitable for routine measurements, providing consistent and accurate results without the need for extensive customization.

Conclusion

The Cary 7000 universal measurement spectrophotometer (UMS) is an effective and user-friendly instrument for assessing the bidirectional transmittance distribution function (BTDF) across visible and near-infrared wavelengths. Its automated features, including detector positioning, sample rotation, and polarization control, streamline the measurement process, ensuring simplicity and reliability. The Cary 7000 UMS consistently delivers precise results with acceptable levels of uncertainty, making it ideal for routine BTDF assessments. Its intuitive interface and seamless integration with Cary WinUV software make it versatile for various optical metrology applications, offering a practical solution for both researchers and industry professionals.

References

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7. Aschan, R.; Manoocheri, F.; Lanevski, D.; Ikonen, E. Measurement of Bidirectional Transmittance Distribution Function in the Visible and Near-Infrared Spectral Range. *Metrologia* **2024**, *61(5)*, 055004. DIO: 10.1088/1681-7575/ad60ca.

A more detailed account of this work was first published in Aschan, R.; Manoocheri, F.; Lanevski, D.; Ikonen, E. Measurement of Bidirectional Transmittance Distribution Function in the Visible and Near-Infrared Spectral Range. *Metrologia* **2024**, *61(5)*, 055004. DIO: 10.1088/1681-7575/ad60ca.

Further information

– Cary 7000 Universal Measurement Spectrophotometer (UMS)
– Cary Universal Measurement Accessory (UMA)
– Agilent Cary WinUV Software for UV-Vis-NIR Applications
– UV-Vis Spectroscopy & Spectrophotometer FAQs

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