

High-Accuracy BRDF and BSDF Characterization of Ultra-Black Coatings

Using Keysight Measurement Services and the REFLET 180S Scatterometer

Executive Overview

Ultra-black optical coatings are increasingly required to suppress stray light in high-performance optical systems such as automotive ADAS sensors, satellite payloads, star trackers, and advanced photonic instruments. Ultra-black coatings, including solutions such as Vantablack® coatings developed by Surrey Nanosystems, are designed to exhibit extremely low reflectance over a broad spectral range.

To properly integrate such coatings into optical systems, angular-resolved optical characterization is essential. Simple hemispherical reflectance values are insufficient to predict real stray light behavior. This application note describes how **Keysight Technologies Measurement Services**, using the **REFLET 180S Scatterometer**, enable accurate, traceable characterization ultra-black coatings through Bidirectional Reflectance Distribution Function (BRDF), Bidirectional Scattering Distribution Function (BSDF), and Total Hemispherical Reflectance (THR) measurements.

Introduction

Stray light is a dominant performance-limiting factor in modern optical systems. Even very small levels of unwanted reflection or scattering can significantly degrade signal-to-noise ratio, contrast, calibration accuracy, and system reliability. This challenge becomes increasingly critical in applications involving low-light detection, high dynamic range sensors, or autonomous decision-making, such as automotive ADAS and satellite imaging.

Conventional black paints and anodized surfaces no longer provide sufficient stray light suppression for these demanding systems. Ultra-black coatings provide a significant improvement by reducing reflected and scattered light. However, due to their extremely low reflectance, these coatings require specialized metrology techniques capable of resolving reflectance levels far below 1% across a wide angular range.

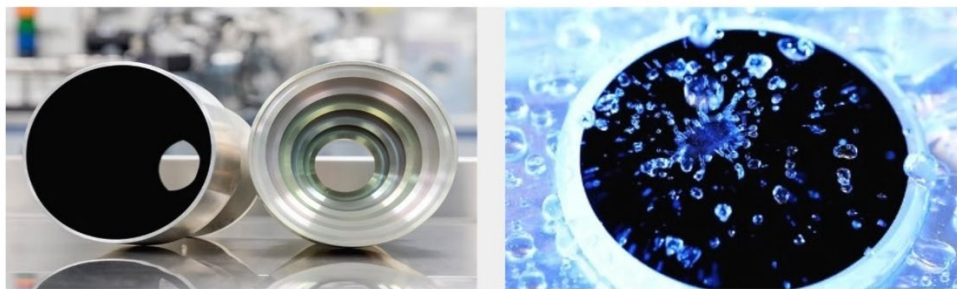


Figure 1. Images of two ultra-black coatings (including Vantablack)

Optical Characterization: BRDF, BSDF, and THR Measurement Principles

The **Bidirectional Scattering Distribution Function (BSDF)** describes how light is scattered (reflected and transmitted) from a surface as a function of both illumination direction and observation direction. BSDF provides a full angular description of reflected/transmitted light, allowing engineers to identify diffuse, glossy, specular, or retro-reflective behavior.

The term **BRDF (Bidirectional Reflectance Distribution Function)** is used when only the reflected light is characterized.

In contrast, **Total Hemispherical Reflectance (THR)** integrates all reflected light over a hemisphere relative to the incident flux and provides a single scalar value. While THR is useful for material comparison, it does not capture angular information and may hide localized scattering peaks that can dominate system-level stray light. For this reason, BRDF measurements are essential for qualifying ultra-black coatings used inside optical instruments.

Optical Properties of Ultra-Black Coatings

Ultra-black coatings achieve low reflectance through engineered surface structures that promote multiple light interactions and absorption. Depending on the product family, these structures may include vertically aligned carbon nanotubes or other engineered surface architectures designed to minimize both diffuse and specular reflection.

BRDF measurements performed on representative ultra-black coatings demonstrate:

- Extremely low reflectance, typically at the 10^{-4} to 10^{-3} level
- Absence of dominant specular reflection peaks
- Stable angular behavior over a wide range of angles of incidence
- Broadband absorption from visible to near-infrared wavelengths

These characteristics make ultra-black coatings well-suited for internal baffles, apertures, sensor housings, and calibration components where stray light suppression is critical.

Also, in view of these characteristics, it is easy to understand that it is a real challenge to measure ultra-black materials. It requires a wide dynamic range and excellent stray light control in the measurement system itself.

Keysight has an optical measurement laboratory that allows it to meet this challenge.

Keysight Measurement Services for Optical Scattering

Keysight Measurement Services address these challenges by providing access to advanced optical scattering instruments operated by experienced BSDF specialists. Customers benefit from:

- Calibrated and traceable measurement setups
- Optimized configurations for ultra-low reflectance materials
- Expert data analysis and reporting
- High confidence results suitable for R&D, qualification, and supplier comparison

This service-based approach allows engineers to obtain high-quality scattering data without the complexity of developing and maintaining in-house BRDF metrology capabilities.

At the core of Keysight's optical scattering measurement service is the **REFLET 180S** Scatterometer. The REFLET 180S is designed for precise angular-resolved BRDF and BSDF measurements, even on extremely low-reflectance surfaces.



Key capabilities of the REFLET 180S include:

- Full hemispherical angular coverage up to ± 90 degrees
- Very high dynamic (10^9) range suitable for ultra-black coatings
- High angular accuracy (0.1°) and repeatability
- Operation in visible and near-infrared spectral regions
- Automated measurement and data acquisition

Figure 2. The scatterometer REFLET 180S and its capabilities

These capabilities allow the REFLET 180S to reliably resolve the reflected signals produced by materials such as Vantablack, enabling accurate characterization under realistic illumination conditions.

Vantablack Measurements and Applications

Measurements

In this application, we characterize Vantablack 310 and Vantablack VB111, which are commonly used in automotive and space applications, respectively. A comparison is made with other black materials measured under the same conditions.

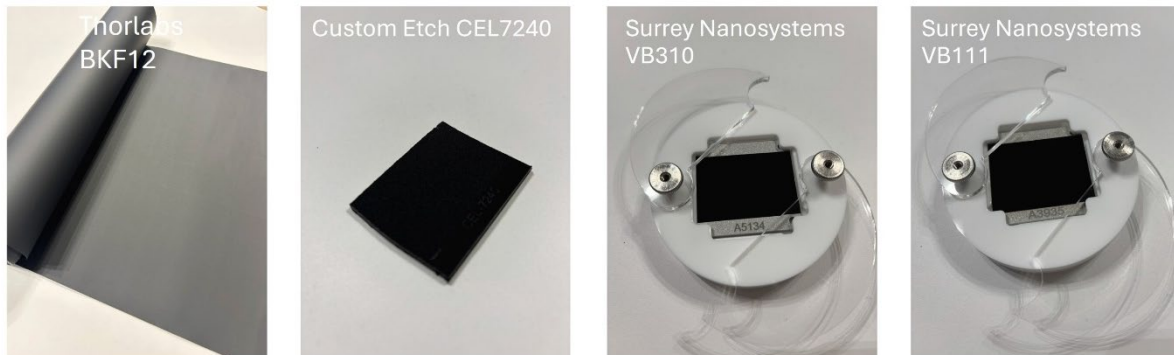


Figure 3. Pictures of the different measured samples

As explained, BRDF measurements are performed with the REFLET. The source illuminates the sample with an angle of incidence of 0° , only one azimuthal plan is measured (in the plane of incidence). The following graph represents the results with a logarithmic scale.

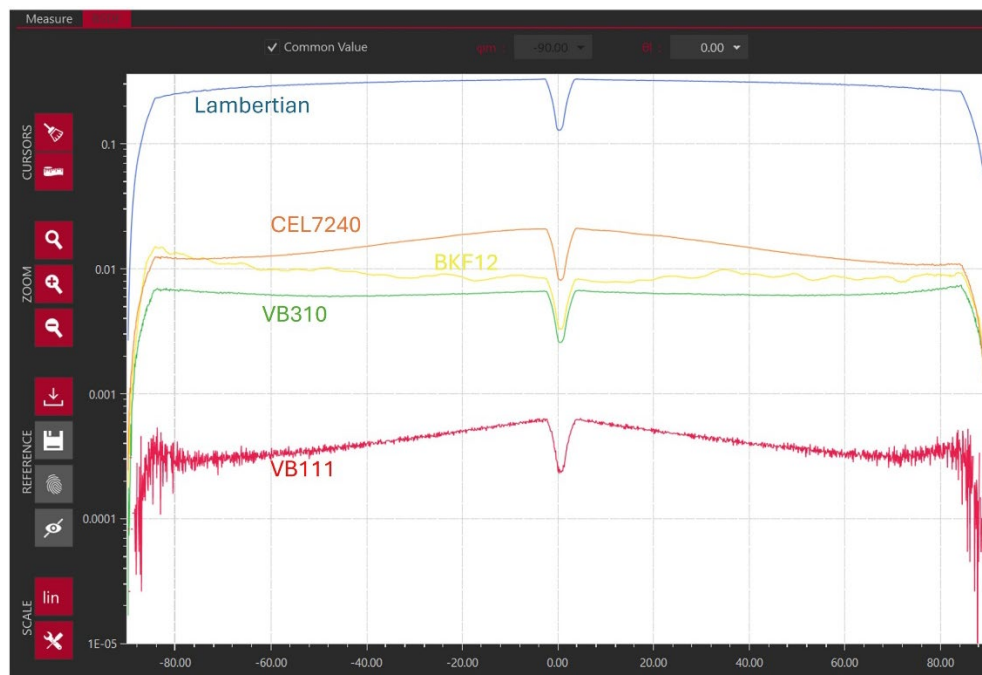


Figure 4. Graph representing BRDF measurements

As expected, the measured ultra-black samples exhibit low reflectance levels with near-Lambertian scattering behavior. This demonstrates the high dynamic range and the ability of the measurement system to detect very low levels of scattering.

We can export these measurement data so that it can be used in optical simulation software (ImSym, LightTools, CODE V...).

Aerospace and Satellite Systems

Star trackers, telescopes, and spaceborne optical payloads rely on extremely low background noise for accurate operation. Ultra-black coatings characterized with BRDF measurements help suppress internal reflections, enhance signal-to-noise ratio, and improve pointing accuracy in harsh space environments.

The example here is a design of a simple triplet with a housing, anti-reflective coating on lenses and optical absorber on the edge. The source is collimated. The measured material is applied on the housing. The different materials measured above are tested.

The result we analyze here is the light collected at the receiver, specifically stray light originating from rays interacting with the housing.

Differences in reflectance behavior between materials can be observed, highlighting the impact of coating selection on stray light performance.

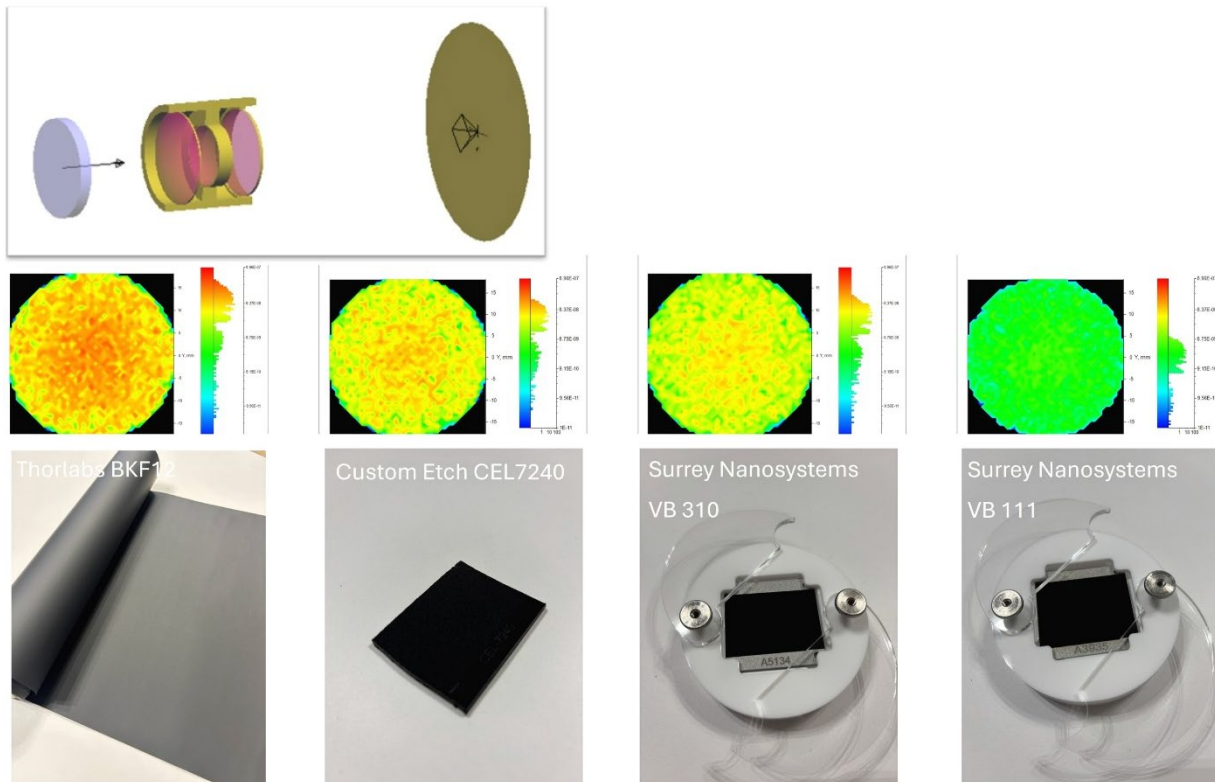


Figure 5. Simulations from samples measurements

Automotive and ADAS Applications

In camera- and LiDAR-based ADAS systems, stray light inside sensor housings can lead to ghosting, reduced contrast, or false detections. Ultra-black coatings, when characterized and validated through BRDF measurements, can reduce internal reflections and improve optical clarity, contributing to improved detection reliability and system performance.



Figure 6. ADAS application

Conclusion

Ultra-black coatings, including solutions such as Vantablack, provide effective stray light suppression, enabling next-generation optical system performance. However, their successful integration depends on **accurate, angle-resolved optical characterization**.

Keysight Technologies Measurement Services, leveraging the **REFLET 180S Scatterometer**, deliver the dynamic range, precision, and traceability required to characterize these materials with confidence. The resulting data supports robust optical design, simulation, and qualification across automotive, aerospace, satellite, and photonics applications.

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