

# Scattering Measurements Guide

## Our Laboratory

Synopsys is equipped with a Photometric Laboratory (a dark room) including:

- Goniophotometers: REFLET 180S
- High specular bench (10 meters)
- Video photometer
- Lux meter
- Luminance meter
- Spectrophotometer
- Integrating spheres: 6" (in gold for infrared), 8" and 40" inch
- Refractometer

The laboratory is new and well equipped. The laboratory temperature and humidity are controlled and regulated to maintain an optimal measurement environment.

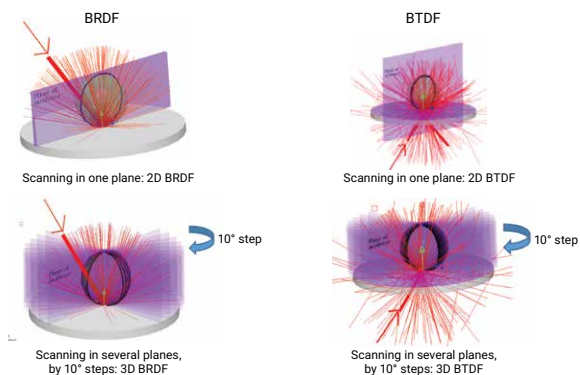
Laboratory class: 10 000 (ISO7) and 100 (ISO5 according ISO 14644-1) for the clean room.



## Our Product Summary

Instruments	Mini-Diff V2	Mini-Diff Pro	REFLET 180S	High Specular
Type	BRDF/BTDF	BRDF/BTDF	BRDF/BTDF	BRDF
Dynamic range	10 <sup>5</sup>	BRDF 10 <sup>5</sup> BTDF 10 <sup>6</sup>	10 <sup>9</sup>	10 <sup>13</sup>
Wavelength range	630nm, 525nm, 465nm, 850nm, 940nm	630nm, 525nm, 465nm	400nm to 1700nm	280nm to 10,6μ
Incident angles	Fixed: 0°, 20°, 40°, 60°	Tunable: 0° to 60°	Tunable: +90° to -90°	Tunable: +90° to -90°
Angular range	Sphere [0° ; 75°] [0° ; 360°]	Sphere [0° ; 75°] [0° ; 360°]	Full sphere	1 plan from -10° to +90°
Angular accuracy	1°	0,5°	< 0.1°	< 0.02°
Repeatability	< 2%	< 2%	< 1%	<1%
Weight	2kg	42kg	80kg	200kg
Advantages	<ul style="list-style-type: none"> <li>• Plug &amp; Play</li> <li>• Easy to use and fast</li> <li>• Portable and compact</li> <li>• Attractive cost</li> </ul>	<ul style="list-style-type: none"> <li>• Dark Box included</li> <li>• Tunable AOI</li> <li>• High repeatability</li> <li>• Attractive cost</li> </ul>	<ul style="list-style-type: none"> <li>• High dynamic range</li> </ul>	<ul style="list-style-type: none"> <li>• Very high dynamic range</li> <li>• Measurement at 0,002° from the specular</li> </ul>
			<ul style="list-style-type: none"> <li>• High precision</li> <li>• High repeatability</li> <li>• Customisable wavelength range</li> </ul>	

## Scattering Measurement: Scanning Planes



## AOI Recommendations

### Minimum Incident Angles

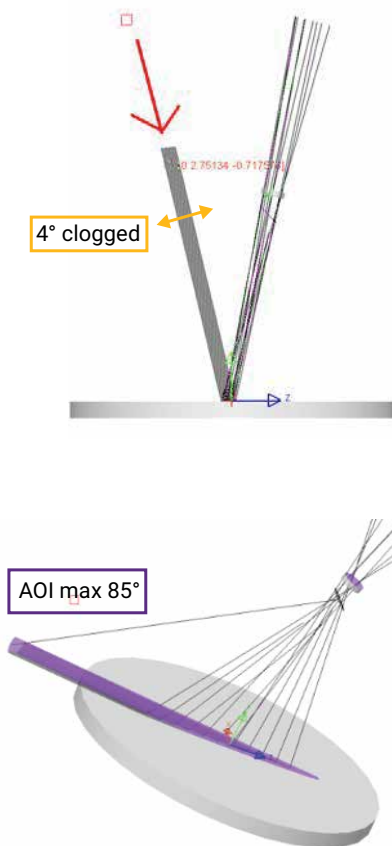
- For BRDF (reflection), when the goniometer is rotating, the detector can obstruct the incident lighting beam
- We do have a 4° dead zone because of:
  - No light coming back on the normal surface for AOI 0°
  - There is not enough distributed light and results are not accurate for AOI < 10°

Therefore, we do recommend AOI > 10°

### Maximum Incident Angles

- Because of “cosine” consideration, a beam of 3 mm at the level of the sample surface becomes an ellipse. The spot size collected by the receiver must be smaller than 12 mm at the level of the sample. For this reason, we limit the maximum incident angle to 85°.
- BSDF characterization is done for incident angles close to the real-world case and can be transferred to an optical simulation software.

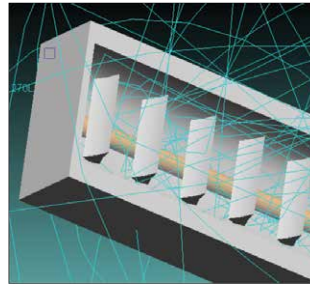
We recommend measuring BSDF for 10°, 30°, 50°, 70°.



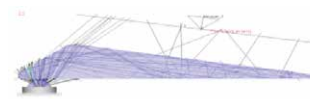
## AOI Examples

Example 1: For a louver, most of the rays have incident angles of 0° to 60° on the reflector.

Example 2: For an automotive speedometer needle, most of the TIR incident angles are between 30° and 90°.



Example 1

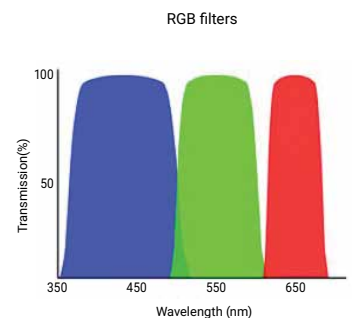
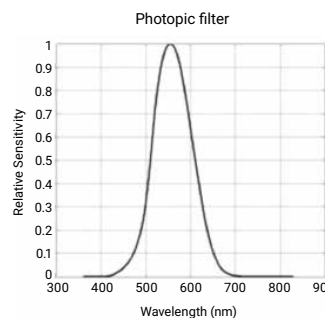


Example 2

## Color and Filtered BSDF Measurements

The BRDF values delivered are the “TOTAL BRDF INTEGRATED” over one wavelength range.

Filter use: We can use different filters as photopic filters, RGB filters or many optical filters (from 300nm to 1700nm each 50nm). Using these filters, we are able to provide a filtered BSDF.



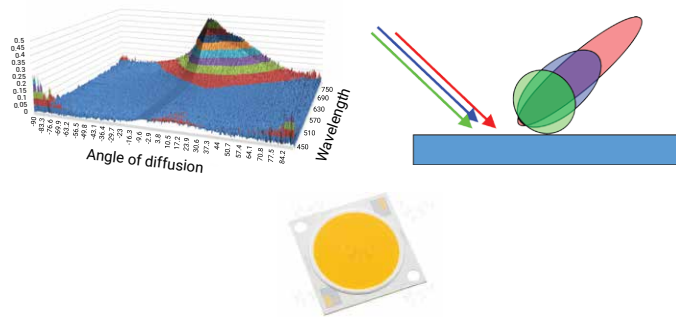
## Spectral BSDF

The scattering distribution can change versus the color (wavelength): applications such as paints, phosphors, lipsticks, etc.

If this is the case, we use a different detector—a spectroradiometer—to measure BRDF or BTDF from 380nm to 760nm. The result is one BSDF distribution each 0,6nm, 1nm, 5nm or 10nm in the wavelength range.

This is a large amount of data that has to be handled in an optical simulation software! We are able to measure 2D or 3D spectral BSDF completely.

However, we do recommend 2D, which is already quite complex.



## BSDF Delivery

- 2D BRDF: In the incident plane, BRDF value each 0.1°, for each incident angle
- 2D BTDF: In the incident plane, BTDF value each 0.1°, for each incident angle
- 3D BRDF: 19 different planes every 10°, BRDF value each 0.1°, for each incident angle
- 3D BTDF: 19 different planes every 10°, BTDF value each 0.1°, for each incident angle
- Files delivered
  - Standard: Text file (not scripted)
  - On demand:
    - LightTools, LucidShape and ASTM (text file) format
    - Support other formats such as ABg or Gaussian/Lambertian
    - Support other software formats, including ASAP, FRED, TracePro, SPEOS, and Zemax

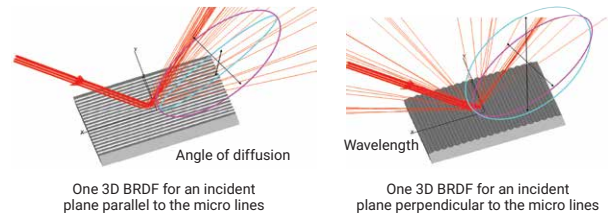
## Anisotropy and Isotropy

### Isotropy

This is the most general case. The sample scatters the light uniformly regardless of the light in an angle of incidence.

### Anisotropy

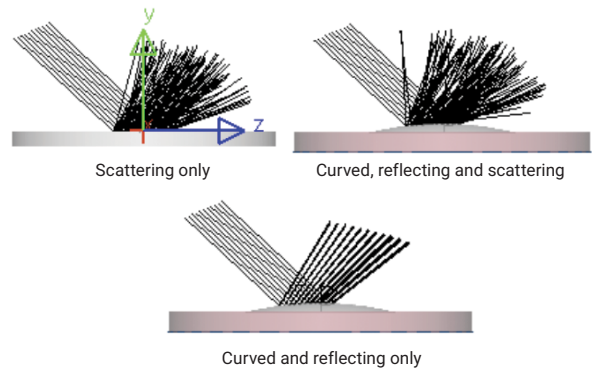
The scattering distribution depends on plane of the incident light. Generally, those samples appear to have stripes on their surfaces. In this case, we can rotate the incident plane by 90°. In many cases, two 3D BRDF measurements are enough.



## Recommendations

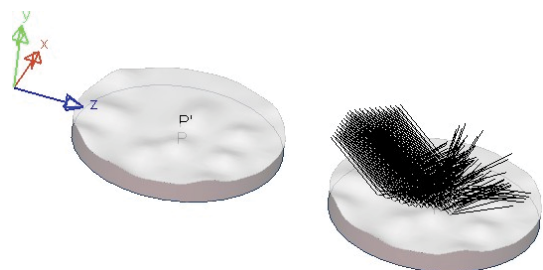
### Flatness of the Sample

The sample has to be flat. Otherwise, a divergent beam is generated at the same time by the scattering and the curvature.



### Beam Size

The beam diameter (spot size on the sample) can be tuned from 1mm to 12mm. In the case of measuring a “hammer” surface, the period of the “hammer” structure should not exceed a value of 3mm.

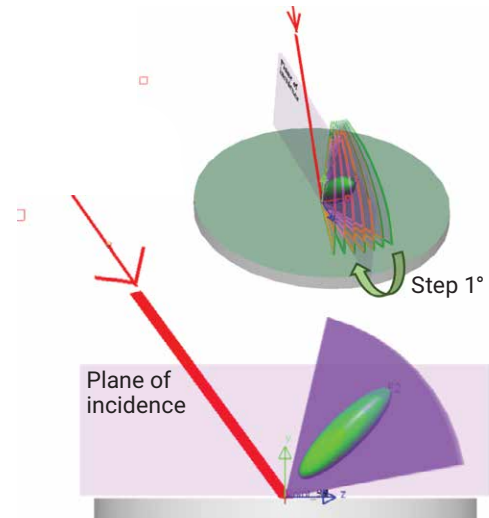


## Near Specular (NS) Reflector

If the diffused beam is  $> 20^\circ$ , we measure one 3D BRDF in each incident plane every  $10^\circ$ . If the diffused beam is between  $5^\circ$  and  $20^\circ$ , we do two bundles of measurements:

- One measurement 3D BRDF with plane every  $10^\circ$
- One measurement near specular with plane every  $1^\circ$

Measurements that we call “Near Specular” have a diffused beam of  $< 5^\circ$ . We scan around the specular beam with a step of  $1^\circ$  between each slice. The Near Specular measurement is done with High Specular Bench. If the divergence of the diffused beam is smaller than  $5^\circ$ , please see “High Specular Measurement” section for an explanation of this method.



## Case of Transmissive Diffusers

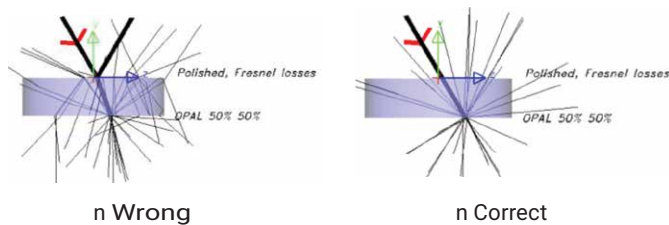
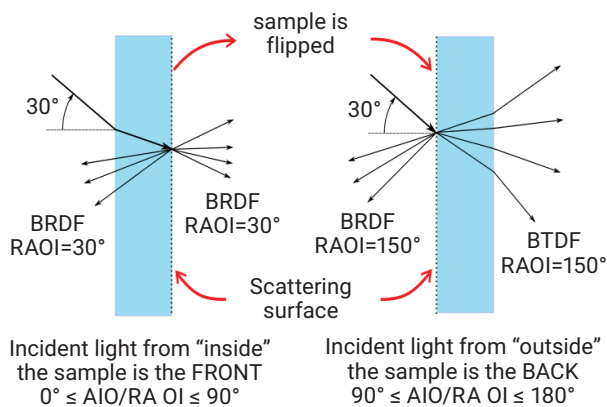
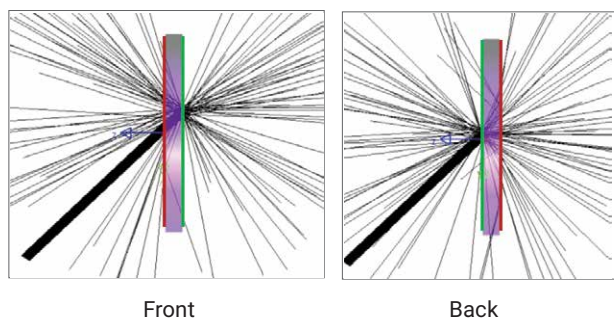
Cases		Measurements
Transmissive diffusers used in transmission only		BTDF
Transmissive diffusers used in transmission and reflection from one side		BRDF and BTDF: Front or Back
Transmissive diffusers used in transmission and reflection used from both sides		BRDF and BTDF: Front and Back
Guided diffuser (TIR)		TIR BRDF (optional TIR BTDF)
Volume diffusers		Volume diffusers: MIE scattering and Gegenbauer

## Case of Diffusers: Definition Back and Front, BRDF and BTDF

If BRDF and BTDF are used and the diffuser is only on one side, (the other side is polished), then there are 2 cases:

- The light hits the polished surface = FRONT first
- The light hits the diffused surface = BACK first

The surface property has to be applied on the surface (left or right) if the measurement is to be used in an optical simulation software. The diffuser must be set up with a refractive index of 1 as the ambient air. If the refractive index is not 1 (e.g., 1.5 as the refractive index of the plastic material for example), the software will propagate the light in the diffuser and will apply Fresnel reflection on the diffused light resulting in additional scattering that does not exist.



## Total Internal Reflectance (TIR) Light Measurements

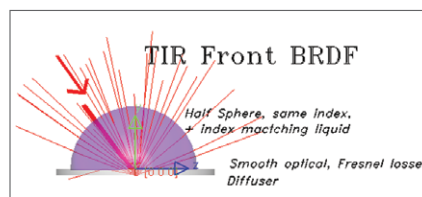
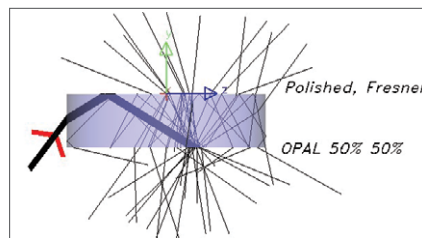
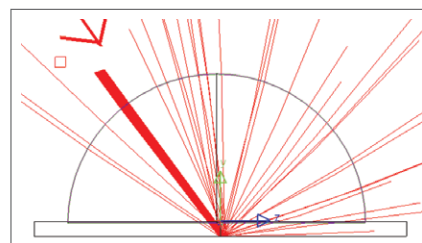
In this case, our focus is on the light diffused "inside" of the light pipe. This requires a special measurement where the top surface (Fresnel losses) has no influence.

Our method is to introduce the light with a hemispherical lens (24mm diameter) aimed towards the surface, to diffuse the light back.

The light is then measured as a normal BRDF or BTDF.

The best sample to measure is a sample where the hemisphere has exactly the same index as the sample. So ideally we want to get a hemisphere with the diffuser on the plane surface.

If this special hemisphere cannot be supplied, we use one of our hemispheres (PC) with an "index matching liquid" between the hemisphere and the sample.



## Total Integrated Scattered Light Measurements

Total Integrated Scatter (TIS) is the ratio of the total power generated by all contributions of scattered radiation into the forward or backward half-space, or both to the power of the incident radiation.

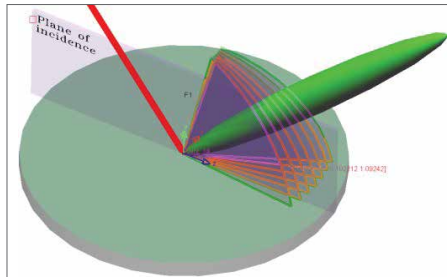
It is not possible to get the TIS from a BSDF measurement only. A goniophotometer scans a limited number of planes, so it does not collect all the scattered light.

In the case of a scatter distribution, with a peak around the specular direction, the sensor may not have the right dynamic to measure the exact maximum values.

Using a given BSDF measurement (BRDF or BTDF), we can calculate the TIS with an accuracy of:

- Around few % for one diffused sample
- Around 5% to 100% for one specular sample

Due to such enormous potential errors, we recommend a highly accurate TIS measurement using an integrating sphere.



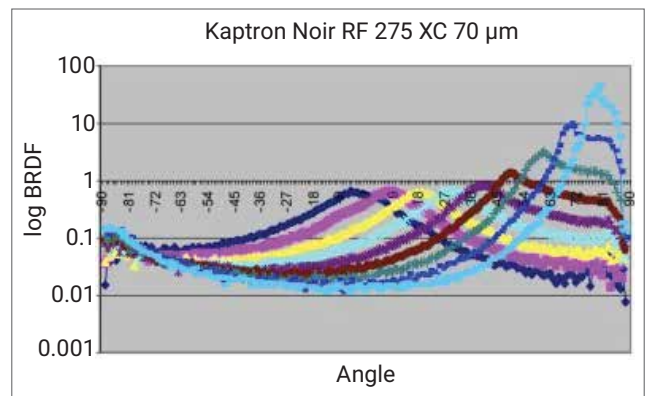
For space programs for example, it is important to evaluate the evolution of the TIS during the manufacturing cycle. Different parameters can affect the actual TIS of the surface. Measuring a bundle of samples following different treatments can help with the knowledge of the most efficient technique:

- Aging
- Cleaning
- Manufacturing

These TIS measurement can be done with:

- White light (from 400 to 1700nm)
- With laser emitting at 532, 638, 808 and 850nm
- With IR laser at 1,55, 3,39 and 10,6µm
- Repeatability +/- 0.03%

Three different integrating spheres are available for samples from 10 to 100mm.



Example of several measured AOI



Aktar type materials

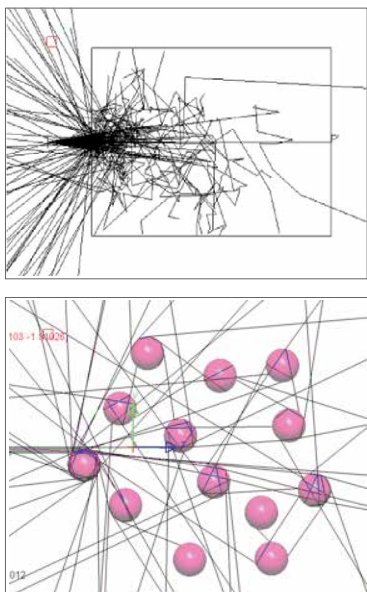
## Volume Scattering Measurements

For volume scattering, we first measure the 2D BTDF of the same sample in four different thicknesses.

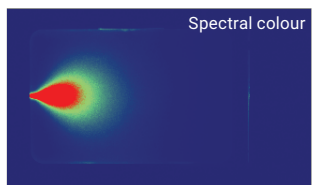
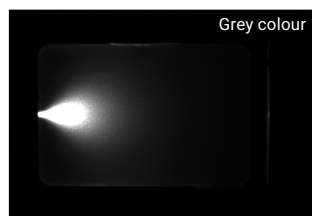
Using these four BTDF measurements, we have developed a special method to find the parameter needed to simulate this material with:

- Gegenbauer model: mean free path, Alpha and g parameters
- Mie Scattering model: radius, density and refractive index of particles. (Upon demand)

Afterwards we verify that the calculated data provides the same simulation results as the measurements.



## Volume Scattering Examples



Picture of a measured sample



Headlights



Flash

## High-Resolution BRDF

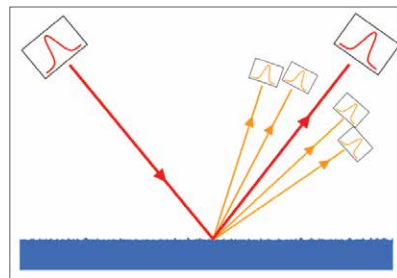
We can measure as close as  $0.02^\circ$  from the specular:

- 2D BRDF, very high dynamic: 1013
- Laser sources at 280, 375, 445, 532, 638 and 850nm and IR lasers at 1,55, 3,39 and 10,6 $\mu$ m

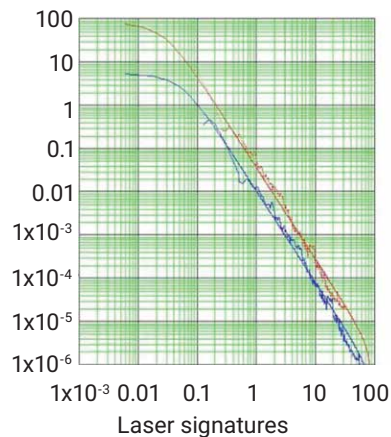
Instrument: bench of 10 meters long

Clean room: class 100 – ISO 5

Application: high polished mirror, quasi specular and a lot more



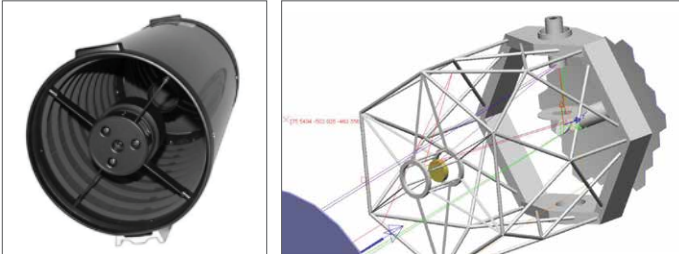
De-convolution of the measurement



## High-Resolution BRDF Examples

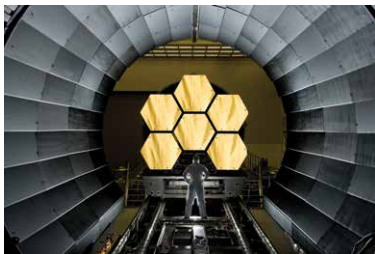
For some space programs, it is important to measure the scattering data of material:

- With a very narrow diffusion for mirrors
- For baffles (edge scattering)
- Or structure



Baffle

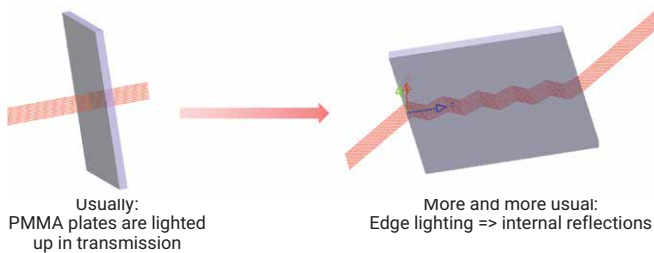
Structure



Mirrors

## Refractive Index Description

- Need to know the refractive index of PMMA
- At different wavelengths because of the dispersion
- Refractive index of PMMA depends on manufacture process
- It is not common to measure the refractive index of samples made in PMMA



Usually:  
PMMA plates are lighted  
up in transmission

More and more usual:  
Edge lighting => internal reflections

## Refractive Index Measurements



- Standard: N-BK7 flat window  $\Phi 1''$
- Thickness 1mm

Wavelength	Theoretical refractive index	Measured refractive index
638nm	1.5149	1.515 ± 0.001
532nm	1.5195	1.520 ± 0.001
445nm	1.5258	1.526 ± 0.001



- PMMA
- Thickness 1mm, 2mm, 3mm & 4mm

Wavelength	Theoretical refractive index
638nm	1.481 ± 0.001
532nm	1.484 ± 0.001
445nm	1.490 ± 0.001

## Refractive Index: Application



Automotive: head and rear lamps



# Refractometer

Instrument	Refractometer
Type	Refractive index
Wavelength	445 nm, 532 nm, 638 nm and 1550 nm
Accuracy	+/- 0.001
Repeatability	<0.5%
Weight	100 Kg
Advantages	<ul style="list-style-type: none"><li>• High precision</li><li>• High repetability</li></ul>

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