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## DEVELOPMENT OF A $\mu$ BRDF GONIOSPECTROPHOTOMETER FOR BRDF MEASUREMENT ON TINY SURFACES

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### Abstract

A  $\mu$ BRDF goniospectrophotometer has been developed at LNE-CNAM. This device performs traceable BRDF measurement with a measurement surface of 30  $\mu$ m of diameter. All angular configuration of measurement belonging to the hemisphere are possible. The spectral range is the visible. This device intends to help to progress in the effort to extent the BRDF metrological scale from the centimetre size to micrometre size. Traceable  $\mu$ BRDF measurement are requested today to validate physical based rendering models used in virtual prototyping and to progress in the comprehension of the appearance of natural material like wool, wood, or leather.

*Keywords:* Goniospectrophotometer, BRDF, tiny sample, micro BRDF, metrology, appearance, virtual prototyping.

### 1 Introduction

The appearance of an object depends not only on material shape and lighting environment but also on the observation distance. As an example, a textile does not look the same when observed from a few centimeters away compared to when observed from several meters away. Viewed from a very close distance, the appearance of each fiber of a fabric is visible, while from longer distances, what is perceived is the full textile pattern.

Currently, the textile industry is developing a “virtual prototyping” approach. The idea is to define the optical properties of the fiber, from which the appearance of the full textile can be simulated, assuming that the weaving scheme is known. The same approach is applied in cosmetics to predict the appearance of hair.

In parallel, the 3D printing industry is progressing quickly. Foreseeably, it will soon be possible to transpose this multiscale approach to 3D printing. Using different types of resin, the optical properties of the polymer wire will be adjustable for the reproduction of real objects or the production of 3D printed objects that will have the same optical properties as the originals. This is particularly interesting when considering the reproduction of natural objects like wool fabrics, wood or leather, for instance.

In order to support this activity on virtual prototyping and 3D printing, a new goniospectrophotometer has been developed at LNE-CNAM (the French Designated Institute for radiometry, photometry and spectrophotometry references) to perform Micro Bidirectional Reflectance Distribution Function ( $\mu$ BRDF) measurement, meaning a traceable BRDF measurement on submillimeter surface.

This paper describes the experimental facility and settings. The first  $\mu$ BRDF measurements realized with our “ $\mu$ BRDF gonio” are also reported here.

## 2 Measurement equation and objectives

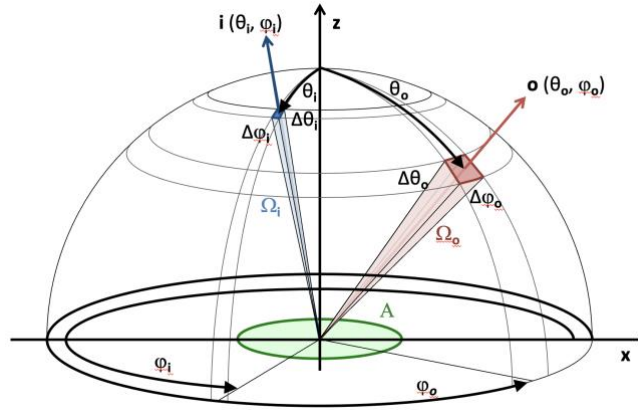


Figure 1 – Geometrical description and notations

Figure 1 outlines the geometric parameters involved in the measurement of the BRDF. Orthogonal unit vectors  $\mathbf{x}$ ,  $\mathbf{y}$  and  $\mathbf{z}$  describe the sample coordinate system with  $\mathbf{z}$  normal to the sample. The direction of the illumination  $\mathbf{i}$  and of observation  $\mathbf{o}$  are respectively defined in this coordinate system by the azimuth angles  $\varphi_i$  and  $\varphi_o$ , and the zenith angles  $\theta_i$  and  $\theta_o$ .  $\Omega_o$  is the solid angle of collection around the direction  $\mathbf{o}$ .

The measured surface has an area called  $A$ . A measurement is performed at a wavelength  $\lambda$ . The BRDF, detailed by Nicodemus in 1977 (Nicodemus, 1977), is defined as the quotient of a surface element radiance in the direction  $\mathbf{o}$  by the irradiance on the medium along the direction  $\mathbf{i}$  and has unit of inverse steradian [ $\text{sr}^{-1}$ ].

In order to express the radiometric quantities, the measurement equation can be written in the form (see Nicodemus et al. 1977 for details):

$$f(\theta_i, \varphi_i, \theta_o, \varphi_o, \lambda) = \lim_{\Omega_o \rightarrow 0} \frac{\Phi_o(\theta_i, \varphi_i, \theta_o, \varphi_o, \lambda)}{\Phi_i(\theta_i, \varphi_i, \lambda) \cdot \cos \theta_o \cdot \Omega_o} \quad (1)$$

where

- $\Phi_i$  is the incident flux in the direction  $\mathbf{i}$
- $\Phi_o$  is the reflected flux in the direction  $\mathbf{o}$

The BRDF definition implies that the facility must be able to orient both the illumination and the detection directions relative to the sample anywhere in the hemisphere above it. The solid angle of collection  $\Omega_o$  must be evaluated. The incoming and reflected fluxes must be measured at a controlled wavelength.

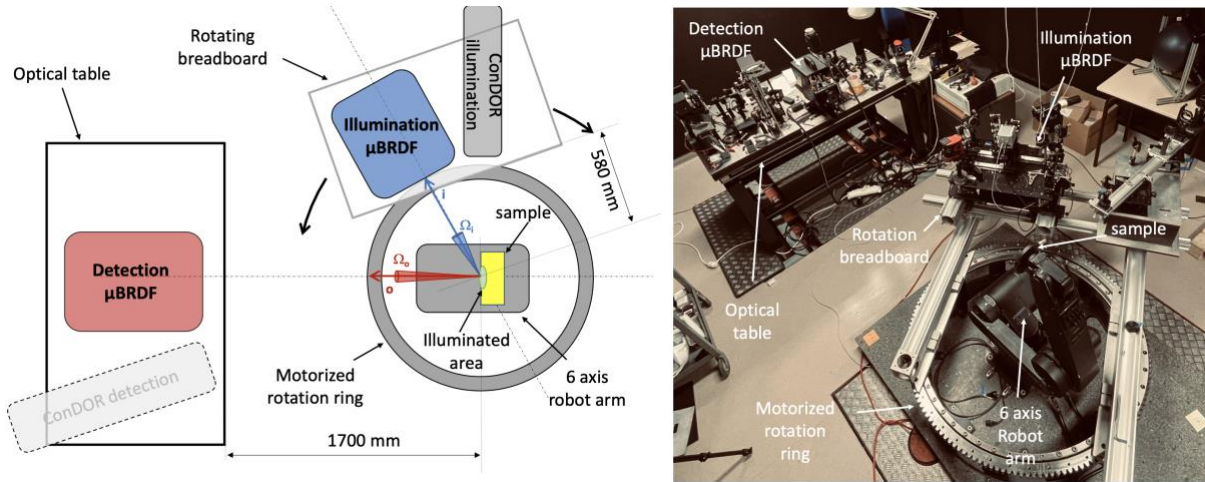
For our  $\mu$ BRDF set up, our objectives are to perform BRDF measurement:

- in the visible,  $380 \text{ nm} < \lambda < 780 \text{ nm}$
- in any direction of the hemisphere
- on a surface  $A$  with a diameter  $\varnothing < 100 \mu\text{m}$
- with an angular resolution  $\Delta\theta < 2^\circ$
- with a spectral bandwidth  $\Delta\lambda < 3 \text{ nm}$

## 3 Description of the system:

### 3.1 General design

We developed a classical goniospectrophotometer composed of a mobile illumination system embedded on a 1 m diameter ring, a 6-axis robot as sample holder and an immobile detection system (figure 2).



**Figure 2 – Left general implementation of the  $\mu$ BRDF goniometer. The illumination is on the rotating breadboard. The detection is on the fixed optical table. The rotation of the table is done with a large motorized ring. The three other rotations are done on the sample, that is mounted at the extremity of a 6 axis robot arm. Right : Picture of the setup in the lab.**

The robot is a RV 12S from Mitsubishi with an on-board load 6-12 kg. It allows to translate the sample along the  $x$ ,  $y$  and  $z$  axis in order to center it on the goniospectrophotometer. It also allows the rotation of the sample around  $x$ ,  $y$  and  $z$ . A fourth rotation is provided by the ring bearing the illumination system. With four rotations, all angular configurations for the illumination  $i$  and observation  $o$  are accessible (Obein, 2005). The angular steps of the stepper motors for the robot and the ring are below  $0,01^\circ$  and don't limit the angular resolution.

### 3.2 Illumination system

Because the illumination system is mounted on a breadboard that is rotating around the robot arm, a gap of 580 mm is imposed by the system and no optical component can be put there (see figure 2, left).

We used an EQ99 Laser Driven Light Source (LDLS) as source. Properties of EQ99 are provided in table 1. The power spectral density of the LDLS is close to that of a Xenon arc which is adapted to our objective to cover the visible spectral range. Our main motivation to use this type of source is that the exitance is high and, compared to a Xenon arc, the light plasma dot is more stable in the space and its size is smaller. The diameter of the plasma size is around  $100 \times 180 \mu\text{m}$ , elliptical.

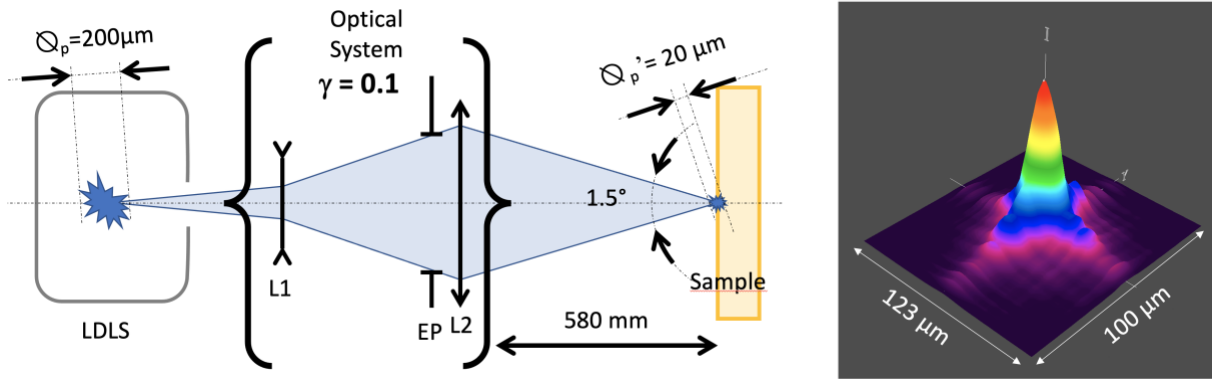
**Table 1 – Properties of EQ99**

Wavelength Range	170nm-2500nm
Plasma size (HWFM) Avg.	$100\mu\text{m} \times 180\mu\text{m}$
Numerical Aperture	0.47 NA
Bulb Lifetime	10,000 hours
Laser Class	Class 1

#### 3.2.1 Optical design:

To achieve an illumination area on the sample with a diameter below  $100 \mu\text{m}$ , we decided to develop an imaging optical system with a magnification of 1/10 (figure 3). The convergence angle has been set to  $1.5^\circ$  to maximize the flux in the system while keeping our objective to have an angular resolution of  $2^\circ$  maximum.

Because of the 580 mm gap between the last lens of the illumination system and the sample plane, a two-lens system had to be adopted and computed. The solution based on "perfect lenses" has been optimized using Zemax<sup>®</sup> software to be compatible with commercial lenses and to minimize the spherical and chromatic aberrations. This optimization was necessary in this situation because the size of the imaged dot approaches the wavelength range.



**Figure 3 – Left: Optical drawing of the illumination system showing the input parameters and the constrained linked to the mechanical design. Right: Best result achieved with a FWHM of 26.7  $\mu\text{m}$  along x axis and 28.9  $\mu\text{m}$  along y axis. The beam shape is a copy of the LDLS plasma power repartition**

The adopted solution consists in a 1 inch diameter diverging achromatic doublet of focal length -50 mm (L1) and a 2 inch diameter converging achromatic doublet of focal length 250 mm (L2). Inter-distance between the lenses is 428 mm. With this system, the image of the plasma is focused 580 mm after L2. The exit pupil (EP) is adjusted with a diaphragm placed 28 mm above L2. The diameter of the diaphragm is set to 12.7 mm in order to have a convergence of 1.5°. That convergence angle defines the angular resolution of the  $\mu$ BRDF gonio.

The full system has been folded in order to fit on a small breadboard of 300x 600 mm

### 3.2.2 Characterisation of the beam:

To optimize the focus of our beam and to validate the system, we used a scanning slit beam-scanner from OPHIR NanoScan. This device measures and analyses the spatial profiles of the beam power with a resolution of 10 nm.

The best that we could achieved is a dot for which 95% of the beam power is within an elliptical shape of 27 x 29  $\mu\text{m}$ . This shape is due to the shape of the plasma inside the LDLS, which is not circular. The power repartition is due to the plasma power, which is not a Lambertian source. A more uniform power profile could be achieved by adding a translucent filter in front of the LDLS. But this would lead to a reduction of flux that is not acceptable for carrying out BRDF measurements.

To sum up, this system allows the illumination of samples with an incoherent broadband beam with more than 95% of the full power being within a disk of 30  $\mu\text{m}$  of diameter and more than 99% of the full power being inside a disk of 100  $\mu\text{m}$  of diameter.

## 3.3 Detection system:

### 3.3.1 Constraints

Because the illumination is broadband, the detection has to be spectral selective. We decided to use the spectroradiometer CS2000 from Konika-Minolta to access the incident and reflected flux. The CS2000 has a spectral resolution  $\Delta\lambda = 0.9 \text{ nm}$  that is better than our objective of 5 nm. It can measure low radiant fluxes, which is appropriate in our situation because our beam is small.

On figure 2, we see that, because of the rotative breadboard, the minimum distance between the spectroradiometer and the sample plane is 1700 mm. The largeness of this distance brings two main difficulties :

- **Entrance pupil:** To keep an acceptable level of flux, the convergence of the illumination has been set to 1.5°. It means that the beam has a 1.5° divergence after the sample. If we want to collect the incident flux by direct measurement of the illumination beam, we need an entrance pupil for the detection of

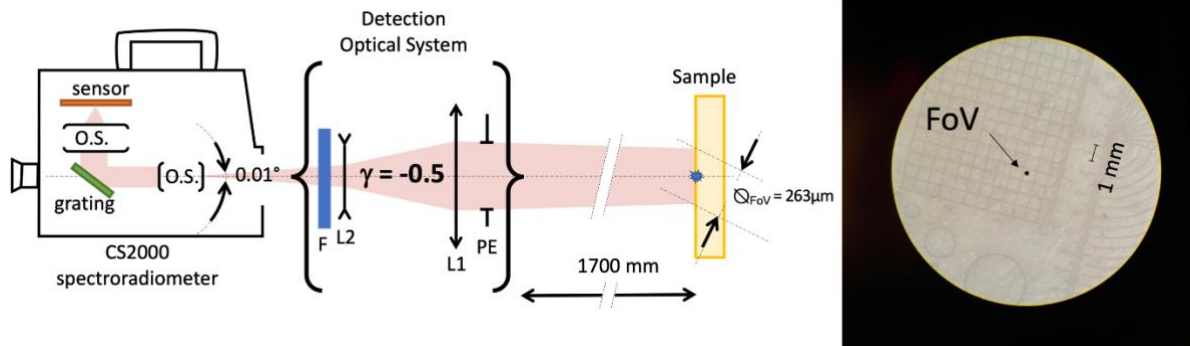
$$\phi_p = 1700 \times \tan 1.5^\circ = 45 \text{ mm} \quad (2)$$

The CS2000 has an entrance pupil that is not large enough with its commercial objective.

- Field of view (FoV) :** the smallest measuring angle of the spectroradiometer is  $0.1^\circ$ , which gives a FoV at 1700 mm of 3 mm. Therefore, the FoV of the detection overfills the illuminated area. In theory, this is not an issue because non-illuminated areas can be ignored in BRDF calculations as they can be considered as black. But in our case, the illuminated area has a 30  $\mu$ m diameter, which is 10 000 times smaller than the observed area of 3 mm diameter. If we consider that a quantity is negligible at a ratio of 1/100 compared to another, this geometry of observation requires the non-illuminated part of the sample to emit less than 1 ppm of the light emitted by the illuminated part. Anyone who has already done BRDF measurement knows that this is almost impossible to achieve, even with a lock-in amplifier. A lock-in amplifier cannot be used with a grating/CCD based spectroradiometer. The only solution to obtain a valid BRDF measurement is to reduce the measuring angle of the spectroradiometer to achieve a FoV that has the same order of magnitude as the illuminated area. We decided on a FoV of 300  $\mu$ m. This allows us to overfill the illuminated area on the sample for zenithal angle up to at least  $80^\circ$  without vignetting.

### 3.3.2 Optical design:

We replaced the commercial optics with custom optics (figure 4, left), comprising a 3-inches diameter converging achromatic doublet of focal length 150 mm (L1) and a 1-inch diameter diverging achromatic doublet of focal length -50 mm (L2). A bluish filter, originally part of the commercial optics, was placed after L2. The entrance pupil of the system is a diaphragm (PE) placed before L1, which controls the aperture of the system and thus, the collection solid angle  $\Omega_o$ . With this system, we expected to obtain a field of view of 300  $\mu$ m for an object located at 1700 mm when using the  $0.1^\circ$  CS2000 field of view setting (which does not correspond to  $0.1^\circ$  anymore with our custom optics). The distance between L1 and L2 is 10 cm and the distance between L2 and the image plane is 20.5 cm. The magnification is  $\gamma=-0.5$ . As the location of the image plane in the CS2000 is not precisely known, the position of the CS2000 is adjusted such that the object is in focus in the viewfinder of the CS2000. The diameter of the area measured by the CS2000, evaluated using a micrometric ruler, is 263  $\mu$ m  $\pm 5\mu$ m (figure 4, right).



**Figure 4 – Left: Optical drawing of the detection system with the 2 lenses allowing to reduce the field of view (FoV) of the CS2000 by a factor 10, while keeping the focal distance at 1700 mm. Right: picture taken in the ocular of the spectroradiometer allowing to measure the real field of view thanks to a micrometric scale place on the sample's plane.**

## 4 Validation:

### 4.1 Measurement on Spectralon white diffuser

We have carried out BRDF measurements with the  $\mu$ BRDF gonio on a 2-inch white spectralon<sup>®</sup> diffuser provided by Labsphere. This sample has been previously calibrated on our reference goniospectrophotometer (Le Breton, 2015) that uses a square measurement area, 9 mm x 9 mm and a detection solid angle of  $\Omega_o = 1.149E-3$  sr (half angle of  $1.1^\circ$ ). Two angular configurations have been tested :  $0^\circ/-5^\circ$  and  $45^\circ/0^\circ$ .

Details and results are reported in table 2 :

**Table 2 – Comparison of BRDF measurements on a spectralon sample**

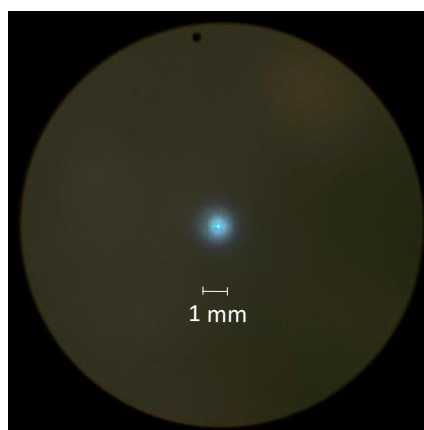
Measurement facility	$\mu$ BRDF	Ref Gonio	$\mu$ BRDF	Ref Gonio
Spectral parameters				
Wavelength [nm]	550	550	550	550
Spectral bandwidth [nm]	0,9	3	0,9	3
Angular parameters				
$\theta_i$ [deg]	0		45	
$\theta_o$ [deg]	-5		0	
$\varphi_i$ [deg]	0		0	
$\varphi_o$ [deg]	0		0	
Beam parameters				
shape	elipsoïdal	square	elipsoïdal	square
size [mm]	0,027 x 0,029	9 x 9	0,027 x 0,029	9 x 9
Solid angle $\Omega_o$ [sr]	5,61E-04	1,15E-03	5,61E-04	1,15E-03
BRDF [sr <sup>-1</sup> ]	0,2266	0,3400	0,2013	0,3206
unc BRDF (K=2) [sr <sup>-1</sup> ]	Not evaluated	0,0102	Not evaluated	0,0096

The two goniospectrophotometers have not the same spectral bandwidth  $\Delta\lambda$  and detection solid angle  $\Omega_o$ . But for a spectralon<sup>®</sup> diffuser, these 2 parameters have a negligible effect as long as they remain at the same order of magnitude, which is the case here (Strothkämper, 2016). Thus, we can assume that, except for the measurement area, the two gonio have comparable settings and the BRDF measurements should be the same. It turns out that the difference between the measurement equipment is significant. Several repetitions have been done with the  $\mu$ BRDF gonio that give the same BRDF values, with fluctuation of few percent that can be attributed to the repeatability of our system.

Two explanations could justify the difference between the 2 measurements.

- > Hypothesis 1 : the  $\mu$ BRDF gonio gives wrong values.
- > Hypothesis 2 : the BRDF of the spectralon<sup>®</sup> changes when the measurement area varies.

A close look at the sample when illuminated with our  $\mu$ BRDF light beam is provided figure 5. At such tiny scale, the sample shows translucency. The light hits the sample at the measurement area, crosses the surface, travels inside the material and is re-emitted in the hemisphere from a point that is outside the field of view of our detection (circular,  $\Omega_{FoV} = 263 \mu\text{m}$ ). We believe that this behaviour explains the fact that the measured BRDF is lower with the  $\mu$ BRDF gonio than with the reference goniospectrophotometer. This behaviour was not expected. The spectralon<sup>®</sup> is not suitable as BRDF standard for  $\mu$ BRDF measurement. Only the measurement of its BSSRDF can be done at this scale.



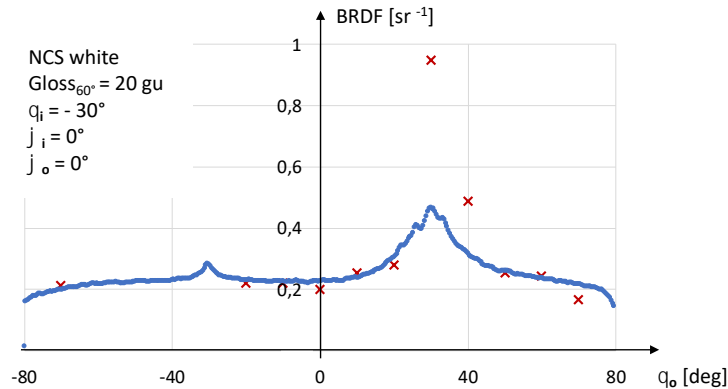
**Figure 5 – Picture of the spectralon® sample taken in the ocular of the CS2000, when illuminated with our  $\mu$ BRDF beam of 29  $\mu$ m diameter, in the angular configuration  $\theta_i = 5^\circ$ ,  $\theta_o = 0^\circ$ . This picture reveals the translucency of the sample.**

## 4.2 Measurement on white NCS sample

To progress in the validation of our equipment, we have used a custom sample developed by NCS in the frame of the Euramet Joint Research Project BxDiff. The sample is made of a white satin coating put on glass substrate. Its size is square 50 mm x 50 mm. Its appearance is isotropic. Its specular gloss at 60° is 20 gu. An inspection of the sample when illuminated by the  $\mu$ BRDF light beam shows that the translucency of this sample is almost zero. Therefore, this sample seems suitable to validate our set up by comparison with a reference goniospectrophotometer.

Unfortunately, the measurement of this sample couldn't be done on the reference goniospectrophotometer this year. Nevertheless, the BRDF of a similar sample from NCS (same coating but spread on paper) has been measured on the reference goniospectrophotometer in 2018. We decided to compare the BRDF values for the two 2 similar samples, in the same angular configurations. Results are plot in figure 6

The agreement between the two devices is good except in the specular direction. This could be foreseen, knowing that the solid angle of detection of the reference goniospectrophotometer is 2 times larger than the one of the  $\mu$ BRDF gonio. This difference plays few when measuring in the diffuse part, but brings significant variations when measuring in the specular direction for glossy samples (Rabal 2019). Deviation of few percents in the diffuse part are acceptable assuming that the  $\mu$ BRDF gonio, because of its extremely small measurement area, has a large uncertainty. The elaboration of the uncertainty budget is in progress.



**Figure 6 – Comparison between the  $\mu$ BRDF setup and the reference goniospectrophotometer. Measurement in the plane of incidence.  $\theta_i = 30^\circ$ . Red crosses : BRDF measured with the  $\mu$ BRDF set up on NCS white coating spread on glass. Blue dots : BRDF measured with the reference goniospectrophotometer on NCS white coating spread on paper.**

## 5 Conclusion:

We have now a goniospectrophotometer that is able to measure the BRDF on a surface with a measurement area of 30  $\mu$ m of diameter. We called this device the  $\mu$ BRDF gonio. It can perform measurement for all the combination of direction of illumination and observation in the hemisphere. The spectral range is 380-780 nm and the spectral bandwidth is 0.9 nm. The conception of the device makes it traceable to the SI. A tentative of validation of the set up by comparison of its measurement with the reference goniospectrophotometer has been done using a classical spectralon® white diffuser. Unfortunately, results can't be exploited because the spectralon® is strongly translucent at this micrometric scale and the measurement of its BRDF doesn't make sense. The validation is still in progress, but preliminary measurement done on a satin white NCS sample are consistent. A comparison of the  $\mu$ BRDF gonio with  $\mu$ BRDF measurement systems developed at other National Metrological Institutes (METAS, IO-CSIC) are planned to progress in the extension of the BRDF scale from centimeter to micrometer size. Multiscale BRDF measurement will also be done on natural material to progress in the understanding of the appearance of natural fibers like wood, wool or leather.

## 6 References:

NICODEMUS, F.E., 1977. Geometrical considerations and nomenclature for reflectance, US Department of Commerce, National Bureau of Standards Washington, DC, USA.

OBEIN G., BOUSQUET R., NADAL M., 2005. New NIST Reference Goniospectrometer. *Optical Diagnostics, Proceedings of SPIE Vol. 5880*

LE BRETON R., GED G., OBEIN G., 2015. Out of plane BRDF measurement at LNE-Cnam using "ConDOR" our primary goniospectrophotometer. *Proceedings of 28th CIE Session*, Manchester, UK, 1401 – 1407.

STROTHKÄMPER C., FERRERO A., KOO A., JANNSON P., GED G., OBEIN G., KÄLLBERG S., AUDENAERT J., LELOUP F., VERDU F., PERALES E., SCHIRMACHER A., CAMPOS J., 2016. Multilateral Spectral Radiance Factor Scale Comparison, *Applied Optics*, **56**(7), p1996-2006.

RABAL A. M., GED G., OBEIN G., 2019. What is the true width and height of the specular peak according to the level of gloss?, *Proceedings of the 29th Quadriennial Session of CIE*, CIE x046:2019, OP88

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