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The measurement of specular gloss using a conoscopic goniospectrophotometer

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Abstract

The measurement of specular gloss using a glossmeter is normalized in the ISO 2813 Standard, which is widely used for many industrial applications. In practice, the principle of the measurement relies on using a primary standard that approximates a perfectly polished back glass surface and an optical design where rectangular diaphragms are used for the source and detection apertures. Any deviation in the refractive index or the polishing level of the standard artefact, or in the machining of the rectangular diaphragms ends in measurement uncertainties. To tackle these issues, we propose to calculate the specular gloss from the bidirectional reflectance distribution function (BRDF) measured using a goniospectrophotometer equipped with a conoscopic detection. With such an instrument, no calibration sample is needed anymore, and the geometry of measurement given in the standard can be applied with good accuracy. The method has been implemented and tested on samples of various gloss values.

Introduction

Specular gloss is measured using glossmeters following the ISO 2813 Standard [1] for surface characterization or inspection in many industries (printing, paint, automotive, packaging, etc). This standard is strongly influenced by the work of Hunter on methods of determining gloss [2] and defines the gloss value, indicated in gloss units (GU), as the "ratio multiplied by 100 of luminous flux reflected from a specimen to that reflected by a glass surface with a refractive index of 1.567 at a wavelength of 587.6 nm in specular direction for a specified reflection angle and specified aperture angles of light source and receptor" [1]. The standard also precisely defines the measurement conditions, illustrated in Fig. 1: 1) The source spectral power distribution corresponds to the CIE illuminant C; 2) The detector spectral sensitivity corresponds to the luminous efficiency function V(λ); 3) The light source aperture dimensions are 0.75° and 2.5° in the directions parallel (θ) and perpendicular (ϕ) to the plane of reflection respectively; 4) The receptor aperture dimensions are 4.4° × 11.7° for the 60° geometry (1.80° × 3.6° for the 20° geometry, 4.0° × 6.0° for the 85° geometry) in the directions parallel and perpendicular to the plane of reflection respectively.

Although the specular gloss definition given in ISO 2813 is straightforward, its application to practical measurements is not easy. The first main difficulty is related to the glass surface described in the standard (referred to as "reference sample" in the following), which must be a smooth glass of optical index 1.567 at the sodium D line (587.6 nm), with the spectral dispersion of the optical index corresponding to the one of black glass. Such a sample does not exist in practice, and primary standards made of BaK5, quartz or Carrara black glass are used with corrections applied to match the theoretical definition [3].

The second main difficulty lies in the glossmeter apertures and associated tolerances. The source and receptor apertures are rectangular, with relatively loose tolerances on their size specified in the ISO 2813 Standard. For example, the tolerance on the source aperture in the direction parallel to the plane of reflection is ±0.1°, which corresponds to 13% of the aperture dimension (0.75°). When the measured sample reflects the light in the specular direction only, like polished glass, those tolerances do not significantly affect the measured gloss value, because the receptor aperture is larger than the source aperture (see Fig. 1) and all the reflected light is measured by the detector, even in case of small misalignment or small errors in the dimensions. However, when the sample reflects light in a diffuse way, the geometrical parameters of the apertures do influence the measured gloss value, because the quantity of light that reaches the detector is impacted by the size, shape, and alignment of the apertures. It has been shown by Leloup et al. that the inter-instrument deviation can be much higher than the precision data specified in the standard when common samples (i.e., other than smooth surfaces) are measured [4]. With the availability of commercial glossmeters at various price points and miniaturized instruments, we can expect significant disparity in the measured gloss values between instruments despite all of them respecting the standard.

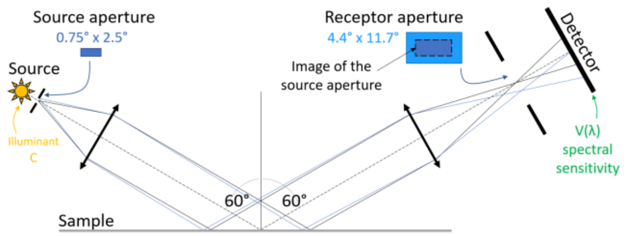

Figure 1. *Glossmeter geometry 60° described in the ISO 2813 Standard.*

In this study, we propose a method for the measurement of specular gloss as defined in the ISO 2813 Standard using a goniospectrophotometer equipped with a conoscopic detection [5]. A conoscope is a device equivalent to a Fourier lens associated with a matrix sensor (a CCD sensor in our case) that images the directional distribution of the light passing through its aperture on the sensor plane. A goniospectrophotometer is an instrument designed to measure the bidirectional reflectance distribution (BRDF) of the sample. Using such device, it is possible to perform an absolute measurement of the light reflected by a sample within the aperture defined in the standard, and to compute the gloss value using the theoretical reflectance of the reference sample described in the standard.

In this article, we first present the material and method used to measure the gloss, limiting our study to the geometry 60°, and show first results obtained on several gloss samples.

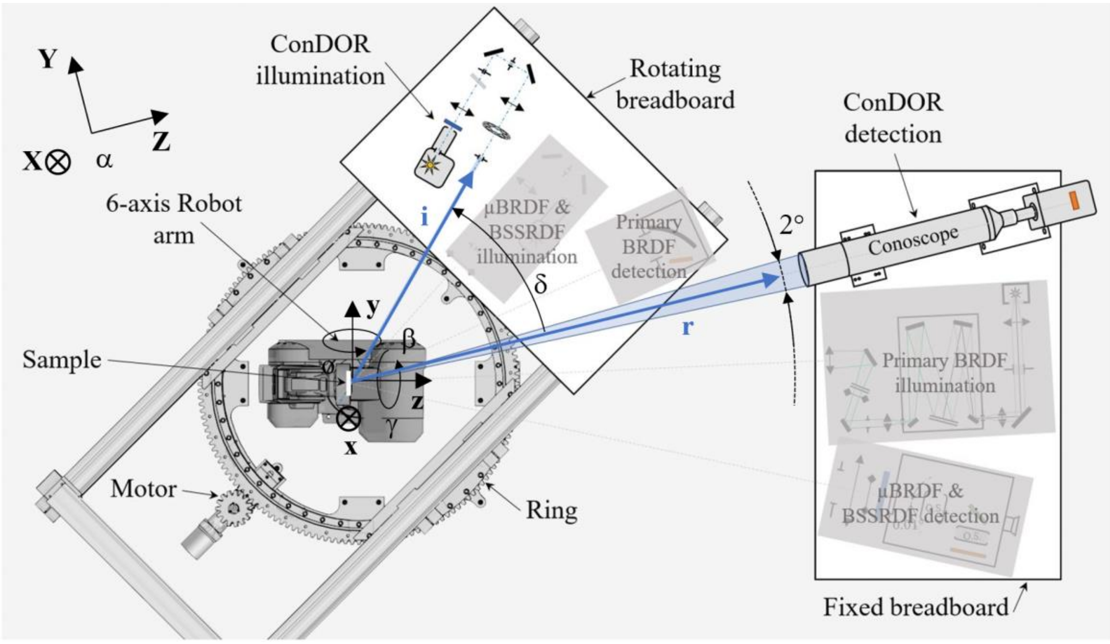

Figure 2. *Schematic representation of the goniospectrophotometer facility showing the mechanical elements, the illumination and the detection used for the measurement of BRDF in a conoscopic mode. The shaded elements are used for other types of measurement on the same facility.*

Material and method

Description of the conoscopic goniospectrophotometer

The conoscopic goniospectrophotometer ConDOR, illustrated in Fig. 2, is an instrument designed to measure the bidirectional reflectance distribution function (BRDF) and the bidirectional transmittance reflectance function (BTDF) of samples. It comprises a collimated source, a sample holder and a conoscopic system as receiver.

The sample is held on a 6-axis robot arm, and the source is located on a rotating breadboard, to illuminate the sample at any incident angle, and collect the reflected light at any observation direction. To perform a measurement for an incident direction $\mathbf{i}(\theta_i, \phi_i)$ and a collection direction $\mathbf{r}(\theta_r, \phi_r)$, the sample is aligned at the centre of the rotation ring (which defines the centre o of the gonio), it is oriented in the angular position (α, β, γ) respectively around the **X** axis of the lab coordinates, and **y** and **z** axis of the sample coordinate system using the robot orientation tools, and the ring is rotated by the angle δ (see Fig. 2). The angles $(\alpha, \beta, \gamma, \delta)$ are calculated as functions of $(\theta_i, \phi_i, \theta_r, \phi_r)$ using formulas detailed in [6].

For the measurement of gloss, the incident direction is $(\theta_i, \phi_i) = (60°, 0°)$ and the collection direction (θ_r, ϕ_r) varies around the direction (60°, 180°) to collect light within the aperture defined in the standard, as detailed in the next subsection.

The light source is a QTH lamp with a color temperature of 2856 K that corresponds to the CIE Illuminant A, with a filter that converts its emission spectrum into CIE Illuminant C. An additional filter is used to adapt the spectral sensitivity of the detection to V(λ) as per the definition of gloss. The filament of the light source is focused on a 100 µm pinhole located at the focal point of a lens of 400 mm focal length. After this lens, the light beam is collimated, and its angular aperture is 0.014°.

The receiver is a conoscope that comprises a CCD camera of 512 x 512 pixels cooled at -72°C with 16 bits of dynamic range and an optical system that images the Fourier plane on the CCD. The field of view (FOV) of the conoscope is roughly 2°, with each pixel corresponding to 0.004°.

Sample measurements

Specular gloss at 60° is measured by illuminating the sample by a source of rectangular aperture 0.75° × 3° and collecting the reflected light at 60° within a rectangular aperture of 4.4° × 11.7°. The dimensions of the receptor aperture are such that all the specularly reflected light is fully collected with a margin around it, as illustrated in Fig. 1. The aperture of our goniospectrophotometer source (0.014°) is much smaller than what is required in the standard. Consequently, to match the definition of gloss, we decided to adjust the aperture of our receiver to keep the same margin between the source image and the aperture border [7], and measure the reflected light within an aperture of 3.65° × 9.2° in the parallel and perpendicular directions respectively. This decision is a first approximation, whose validity depends on the sample reflectance properties, namely the sensitivity of its BRDF to variations of the incident direction.

As the angular FOV of our instrument is only 2°, we must perform multiple measurements and merge them together to fully cover the rectangular aperture of 3.65° × 9.2°. Figure 3 shows the rectangular aperture over which the reflected light must be measured in the (θ, ϕ) Lambert azimuthal equal-area projection coordinates system of the sample. This aperture corresponds to a rectangle in the plane perpendicular to the direction (θ_r, ϕ_r) = (60°, 180°), but is not rectangular anymore once projected on the sphere, as the borders of the rectangle do not correspond to constant ϕ values. The centres of the 17 ovoids shown on Fig. 3 give an example of geometries of measurement that can be performed to cover the complete aperture. A denser mesh of the aperture can also be used to improve accuracy, to the detriment of acquisition time.

After aligning the sample at the centre of the gonio, the measurement process is as follows: First, the source is placed

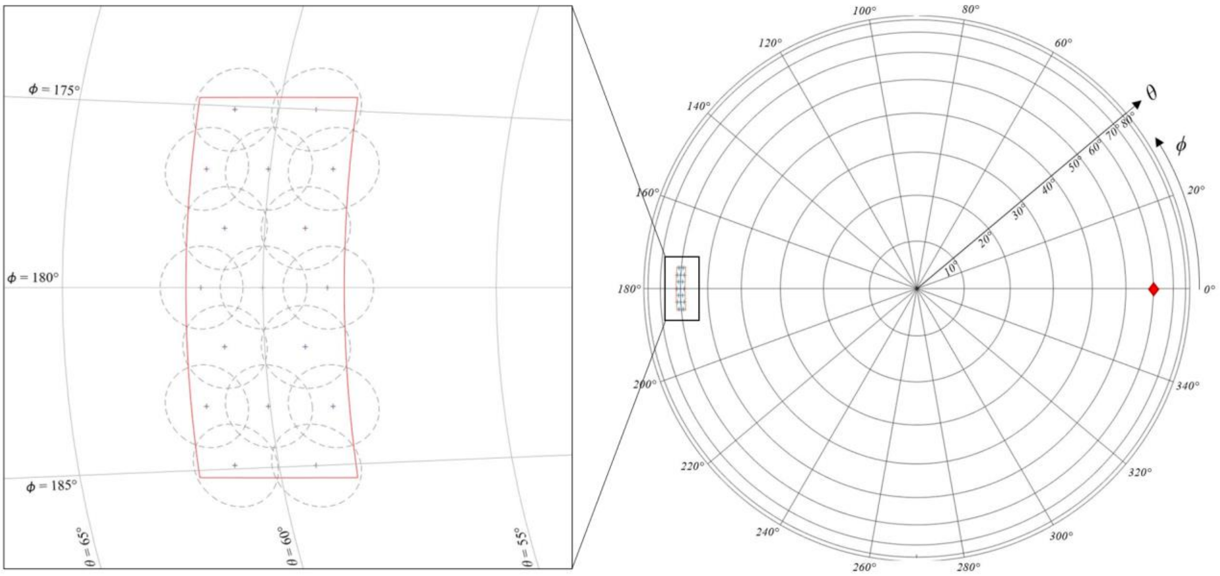

Figure 3. *Representation in the (θ, ϕ) Lambert azimuthal equal-area projection coordinates system of the sample (right: full view, left: zoom in) of: the direction of the source (red diamond), the 3.65° x 9.2° aperture (red curve), 17 positions of the conoscope that can be used to map the receptor aperture (black crosses), and of the corresponding conoscope FOV for each position (dotted gray ovoids).*

directly face to the conoscope, the sample is moved out of the source direction, and the image corresponding to the incident light flux I_{source} is captured with its associated dark signal $I_{k,source}$. Then, the source and the sample are placed in their measurement positions, and the light flux reflected by the sample is captured on an image I with its associated dark signal I_k. This is repeated as many times as there are measurement positions. Finally, the incident light is measured again.

The incident flux measurement is performed with a calibrated neutral density filter placed before the source aperture, to not saturate the camera sensor. For the reflected light measurement, the integration time of the camera is adjusted depending on the sample type. As the camera's CCD is cooled down, the integration time can be as long as 300 seconds without having significant noise issues. It is useful for samples with a low gloss value, for which a very small quantity of light reaches each pixel of the sensor, as the incident light is reflected in a wide peak. On the contrary, for very glossy samples, the specular peak is narrow and a very short exposure time is necessary to avoid saturating the camera sensor. A high dynamic range (HDR) acquisition, obtained by combining several images captured at several integration times, is then necessary to cover the full dynamic range of the specular peak.

Calculation of the gloss

The gloss value (unit GU) can be expressed as follows,

$$G = \frac{100}{\rho_0(\lambda_D)} \cdot \frac{\varphi_{sample}}{\varphi_{source}}, \tag{1}$$

where φ_{sample} is the luminous flux reflected by the sample in the rectangular aperture, φ_{source} is the luminous flux incident on the sample and $\rho_0(\lambda_D)$ is the reflectance of the standard plate of optical index 1.567 at 587.6 nm. For the 60° measurement geometry, $\rho_0(\lambda_D) = 0.100056$ [8].

To compute the gloss value, the images acquired using the conoscope are merged to obtain a larger map with pixels expressed in camera counts, which are proportional to irradiance. The images are merged by identifying the location of each pixel of each image in the plane of the rectangular aperture. The reflected flux φ_{sample} is proportional to the sum over the rectangular aperture R of the pixels signal $I_{i,j}$ corrected from their associated dark signal $I_{k,i,j}$ and normalized by their integration time $t_{i,j}$.

Similarly, the incident flux φ_{source} is proportional to the sum of the pixels $S_{i,j}$ of the image obtained for the source direct measurement subtracted from the associated dark signal $S_{k,i,j}$, divided by the integration time t_{source} and by the transmittance of the neutral density filter used T_{ND}. Finally, the gloss value is:

$$G = \frac{100}{\rho_0(\lambda_D)} \cdot \frac{\sum_{(i,j)\in R} (I_{i,j} - I_{k,i,j}) / t_{i,j}}{\sum_{(i,j)\in source} (S_{i,j} - S_{k,i,j}) / t_{source} / T_{ND}}. \tag{2}$$

Measurement results

Samples and measurement parameters

The samples used in this study are three NCS gloss samples (A, B, and C) made of acrylic or nitrocellulose paint on glass. Sample A is white, samples B and C are black. Their nominal gloss values at 60° are 20 GU, 40 GU, and 75 GU for samples A, B, and C, respectively.

A minimum of 17 measurements are necessary to cover the rectangular aperture, as illustrated in Fig. 3. However, for our first measurements, we decided to use a denser mesh with 21 measurements (3 × 7) regularly spaced with a step of 1.2° in the direction parallel to the plane of reflection, and a step of 1.3° in the direction perpendicular to the plane of reflection. In that way, only the pixels located at the centre of the FOV are used.

The measurement parameters (integration time and source aperture) are chosen to maximize the signal-to-noise ratio, with pixel values well distributed over the 16 bits dynamic of the sensor, integration times above 1 s to avoid linearity issues and below 120 s to limit the overall measurement time. For matt samples, an integration time of 120 s is not sufficient to obtain enough signal on the camera. In that case, the angular aperture of the source can be increased to obtain more incident flux on the sample. The diameter of the source pinhole (and therefore the source angular aperture) can be increased while keeping a low error on the specular peak measurement following the recommendations given in [9]: to measure the peak width with less than 5% of error, the aperture must be lower than 1° for matt samples (A), 0.66° for semi-matt samples (B) and 0.05° for glossy samples (C). It should be noted than 5% of error on the peak width corresponds to a lower error or the computed gloss value, as it is the total flux comprised in the rectangular aperture that matters.

The pinhole diameters chosen to measure the four samples largely respect the criteria listed above, with a pinhole of 1000 µm (0.14°) used for samples A and B, and a pinhole of 200 µm (0.028°) used for sample C. Regarding the integration time, it is adjusted depending on the quantity of incident light and on the reflection properties of the sample. For glossy samples, HDR measurements are performed to increase the dynamic range of the measurement.

The measurement parameters are summarized in Table 1.

Table 1. Measurement parameters.

Sample	~ GU_{60}	Pinhole diameter	t_{expo} source	t_{expo} sample
A	20	1000 µm	1 s (ND2.5)	120 s
B	40	1000 µm	1 s (ND2.5)	HDR: 12 s, 24 s, 48 s, 96 s
C	75	200 µm	2 s (ND2.5)	60 s at the center, 120 s otherwise

Measurement results and gloss values

Figure 4 shows the 21 images obtained at the 21 geometries of measurement used to determine the gloss value for sample C. Figure 4.left shows the images before processing, and Fig. 4.right shows the map that corresponds to the rectangular aperture of dimensions 3.65° x 9.2°, obtained after combining the images.

Figure 5 shows the reflected flux measured in the rectangular aperture for samples A, B and C, normalized to the incident flux. The three normalized flux maps are displayed using the same logarithmic scale to be able to visually observe the relationship between the gloss value and the shape of the specular peak. Indeed, we observe on Fig. 5 that the specular peak is narrow and over a large dynamic range for sample C, the glossiest sample, while it is very wide and more uniform for sample A, the most matt sample.

Table 2. Gloss values obtained with the goniospectro-photometer method, compared to values obtained using a commercial glossmeter.

Sample	GU_{60} gonio	GU_{60} Rhopoint IQ
A	17.0 ± 0.5	18.9
B	43.2 ± 1.0	43.9
C	71.4 ± 3.0	69.9

The gloss values for each sample are obtained by applying Eq. (2) and summarized in Table 2. For comparison, gloss values obtained using a commercial glossmeter (Rhopoint IQ glossmeter, calibrated on a BYK Gardner semi-gloss tile) are also shown in Table 2.

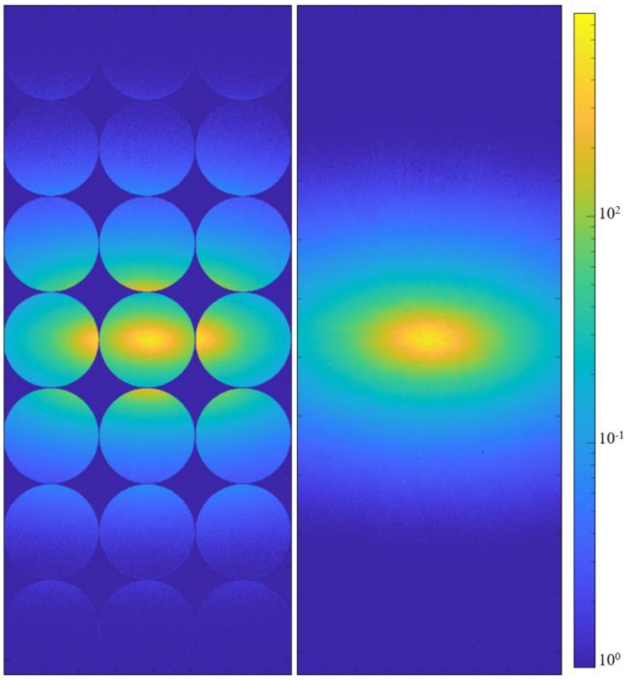

Figure 4. *Sample C (glossy), measurement results before processing (left) and after merging the different measurements (right), in camera count/s, displayed in log scale.*

The measurement uncertainties mainly come from the uncertainty on the direct source measurement. In a first approximation, it is evaluated at ± 0.5 GU for sample A, ± 1.0 GU for sample B and ± 3.0 GU for sample C.

Discussions and conclusion

In this study, we have shown that the specular gloss defined according to the ISO 2813 Standard can be measured using a goniospectrophotometer equipped with a conoscope, without the need to use a calibration tile. This paper shows first results that are compatible with the values measured using a commercial glossmeter, but they need to be completed by a full metrological evaluation of the method to estimate the measurement uncertainties.

The good implementation of this method relies on a good control of the geometry of measurement for an accurate measurement of the specular peak within the aperture defined in ISO 2813. It also relies on the ability to accurately capture the incident flux and the reflected signal with a high dynamic range and a low level of noise and stray light. In particular, we expect a significant contribution of the error on the incident flux measurement to the gloss value uncertainty. Using a camera-based instruments to perform those measurements with a metrological approach can be challenging. HDR measurement methods provide the required dynamic range, but it seems that the HDR results are prone to variations depending on the parameters used for the HDR reconstruction. Research on the traceability of HDR luminance imaging are currently under progress in the Joint Research Program 21NRM01 "HiDyn" [10]. Questions

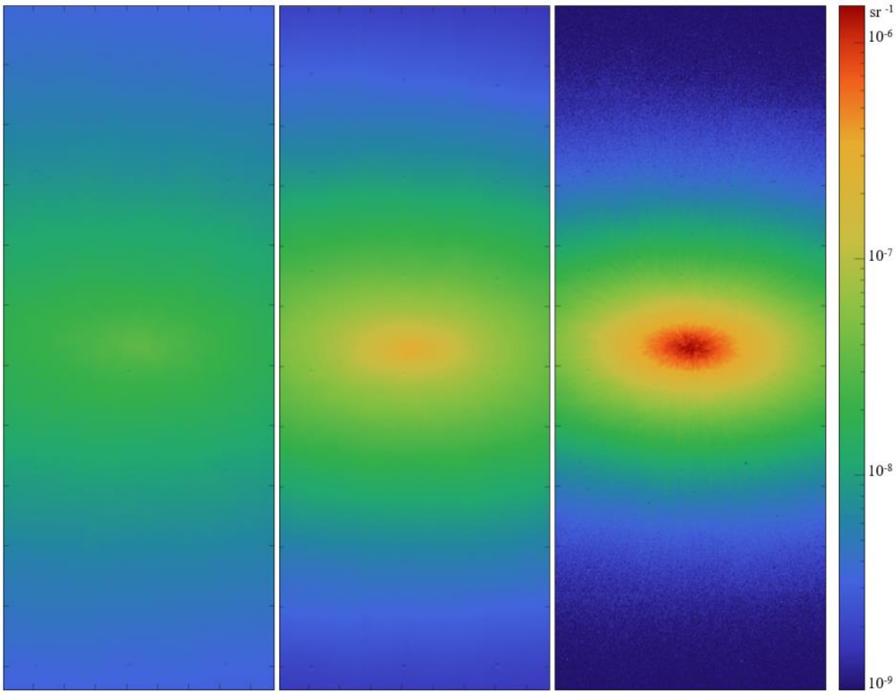

Figure 5. *Reflected flux in the rectangular aperture for samples A, B and C, normalized to the incident flux and displayed with the same logarithmic scale.*

concerning the post-processing applied to reduce the noise observed when the light signal is low also raise concerns regarding the measurement uncertainties. These issues will be further investigated in a future work.

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Author Biography

Lou Gevaux received her B.S. and engineering degree from Institut d'Optique Graduate School (2014), and her PhD on the topic of 3D-hyperspectral Imaging for the human face from the University of Lyon (2019). She currently works at the Conservatoire National des Arts et Métiers (Paris), in the LNE-CNAM lab, the French designated institute for radiometry, photometry and spectrophotometry references. Her research focuses on the metrological measurements of material appearance.