FINAL PUBLISHABLE REPORT

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1 Overview

The commercial success of a product is often dependent on its aesthetic appearance. For this reason, different industrial sectors e.g. automotive coatings, cosmetics, printed materials, are continuously looking to develop new attractive visual effects. This project focused on the pre-normative work required to clarify how measurements on standard materials and surfaces exhibiting goniochromatism, gloss, sparkle, and visual effects should be carried out. This enabled a reliable comparison of results provided by different measurement devices and will lead to better control of the visual effects of products.

2 Need

Objects are identified through their shape, size and “visual attributes” i.e. colour, gloss, translucency and texture. These attributes define the appearance of the objects. For industrial manufacturers, the appearance of a product is important at the quality control level (because the visual appearance informs the manufacturer on the constancy and reproducibility of its production) and at the commercial level (because the appearance of a product directly influences the customer and the purchase decision). Within the last 25 years, substantial effort has been undertaken by industrial manufacturers to create attractive and sophisticated visual effects. While most of the production in the 80s was isotropically coloured and with simple gloss attributes, currently the production is satin, iridescent, brushed, textured or sparkle. Current standards on colour measurement (ISO 11664) and gloss measurement (ISO 2813) are not adapted anymore to the characterisation of these sophisticated visual effects that require a bidirectional measurement approach of the reflectance and/or an image-based approach of the radiance. No standard exists for Bidirectional Reflectance Distribution Function (BRDF). No protocol exists for sparkle characterisation. Without standardisation and standard methods in this field, manufacturers of spectrophotometer systems and NMIs are developing their own instruments, using different optical parameters and methods of measurement. This leads to a lack of comparability in the BRDF and its derived quantities like goniochromatism, gloss or sparkle. For this reason, in 2016 the CIE (Commission Internationale de l´Éclairage) decided to initiate work on BRDF through TC2-85.

3 Objectives

This project aimed to clarify how BRDF measurements on both classical surfaces and surfaces exhibiting goniochromatism, gloss and/or sparkle visual effects, should be carried out.

The scientific and technical objectives of this project were to:

1. Propose standard parameters for the measurement of the BRDF of particular materials and optical surfaces in the visible range in order to improve the traceability to the SI between users and NMIs, and therefore to allow for better agreement between commercial goniospectrophotometers. The focus will be on i) settings of solid angles, ii) illuminated and measured areas, and iii) convergence of light beams. In addition, to provide guidance on how to sample the BRDF space efficiently and to propose a minimum number if measurement geometries according to the appearance properties of the specimen.

2. Propose arrangements for data handling and processing for BRDF measurements when a large amount of data is obtained.

3. Propose a new method for gloss measurement that correlates with visual perception. The contribution will be based on i) reflectance measurements, ii) visual evaluations and iii) definition of a standard gloss observer.

4. Propose a consensual definition of sparkle and graininess measurands and define procedures for their measurement in correlation with visual scales for sparkle and graininess.

5. Facilitate the uptake of the technology and guidance developed in the project by the measurement supply chain, e.g. instrument manufacturers and end-users, e.g. automotive, cosmetics, pigments, packaging and 3D printing industries. In addition, to contribute to the standards development work

of international standardisation bodies, e.g. CIE. Dissemination of project results will take place as early as possible to establish a standardised approach.

4 Results

4.1 Objective 1: Standard parameters for measuring BRDF

The impact of using finite intervals for the measurement area, irradiation and collection apertures, and solid angles has been examined by CSIC for the measurement of BRDF.

4.1.1 Theoretical approach to evaluate the limitations of experimental systems and to account for the relative error due to finite intervals.

The BRDF, depending on the reflected spectral radiance of the sample, is by definition a measurand which theoretically has to be determined by using infinitesimal solid angles. Real BRDF measurements, however, require finite-size apertures and measurements areas, and, therefore, the realisation of the bidirectional geometries introduces an error. The consequence of using a finite measurement area and finite irradiation and collection solid angles is that the BRDF is evaluated as a weighted average over a set of pairs of irradiation and collection directions. As long as this weighted average coincides with the real BRDF with a negligible deviation, the measurement conditions can be considered adequate. The usage of finite apertures limits the BRDF measurements when its angular distribution has a curvature in the measuring angular range, being more critical when the relative variation of the distribution is higher. Specular reflection is an important case, but it is not the only one.

The error due to finite-intervals was calculated as the relative difference between a biconical integration of the BRDF and the actual BRDF. The biconical integration of the BRDF is called the biconical reflectance factor, and describes the reflectance when the sample is irradiated with a conical geometry (finite, not vanishing solid angle) and the reflected radiant flux is collected with conical geometry, which is the real measurement condition. Mathematically, it can be expressed as:

$$f_{\mathrm{r,m}}(\mathbf{r}_{\mathrm{i}0},\omega_{\mathrm{i}};\mathbf{r}_{\mathrm{r}0},\omega_{\mathrm{r}}) = \frac{1}{\Omega_{\mathrm{i}}\Omega_{\mathrm{r}}}\int_{\omega_{\mathrm{i}}}\int_{\omega_{\mathrm{r}}}\int_{\mathrm{A_i}} S(\mathbf{r}_{\mathrm{i}};\mathbf{r}_{\mathrm{r}})\mathrm{d}A_{\mathrm{i}}\mathrm{d}\Omega_{\mathrm{r}}\mathrm{d}\Omega_{\mathrm{i}}, \tag{1}$$

In this expression, A_i is the measurement area, Ω_i, and Ω_r are the projected irradiation and collection solid angles, ω_i and ω_r are, respectively, the corresponding irradiation and collection solid angles, $\mathbf{r}_{i0}$ and $\mathbf{r}_{r0}$ are the central irradiation and collection directions defined in the measurement, $\mathbf{r}_i$ and $\mathbf{r}_r$ denote general irradiation and collection directions, and S is the bidirectional reflectance distribution function of the sample.

All solid angles involved in the measurement were parametrised using the half angles (κ), and the bidirectional reflectance distribution function was parametrised using a factor β, which was related with the angular curvature (the lower it is, the lower the impact due to finite-intervals).

By numerical calculations, it was possible to obtain an equation relating the relative error due to the finite-intervals impact and two main factors: (1) the scattering distribution function of the surface, and (2) the geometries of the incident and collected radiant fluxes. This equation can be regarded as a general rule for experimentalists, and it will help in the design of instruments devoted to measure BRDFs that present strong dependence with incidence and collection geometries, such as those of glossy or iridescent surfaces. For more detail, please read the article “Theoretical evaluation of the impact of finite intervals in the measurement of the bidirectional reflectance distribution function” (see here).

Example of results of numerical calculation are shown in Figure 1.

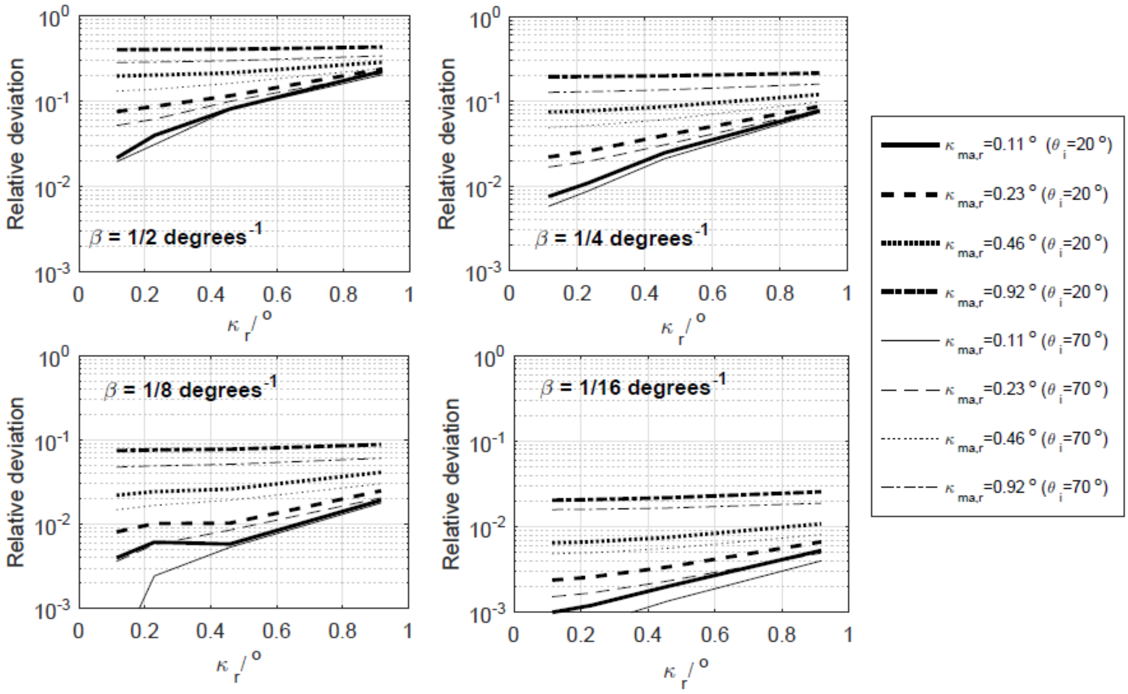


Figure 1. Relative deviation between the actual BRDF of four different samples (different values of β) and the measurement with different finite-intervals sizes (different values of κ). Results were obtained by numerical calculation.

4.1.2 Determinations of the settings required to access a reliable BRDF of the surface in the specular direction according to its gloss level measured

When evaluating the gloss of a surface, observers always look in and around the specular direction. For this reason, it is assumed that gloss takes its origin in the specular peak of the BRDF of the surface. For a glossy surface, the BRDF shows a sharp peak. For matt surfaces, the peak is spread and small. In order to progress in the comprehension of gloss and to propose new ways for its measurement, it is necessary to measure the specular peak.

But correct measurement of the BRDF in the specular is not trivial. As a matter of fact, in order to get a valid measurement of the BRDF, the solid angles of illumination and of collection of the measurement device must be negligible according to the angular variations of the BRDF of the sample. This is the case in most of the measurement situations except when measuring the specular peak of glossy samples.

For glossy samples, the specular peak can be narrow and reach a Full width at half maximum (FWHM) of 0,5° at the top of the gloss scale. Valid assessment of this peak request then a measurement setup that will have an illumination and collection solid angles small enough in front of these variations. If measured with a larger aperture, the result will not reflect the specular peak, but the convolution between the peak and the apparatus function of the goniospectrophotometer.

The project used Conoscopic Device for Optical Reflectometry (ConDOR). ConDOR is a goniospectrophotometer developed at CNAM. It uses a mobile collimated illumination with a divergence that is adjustable and can drop to 0,028°. The detection combines a Fourier optic with a cooled digital camera and allows to measure the radiance with a solid angle of 0.004°. In ConDOR, the convergence of the illumination limits the angular resolution.

In this study, the 6 samples of the Natural Colour System (NCS) gloss scale have been measured. For each sample, the zenith angle of illumination was $\theta_i = 30°$. The azimuth was $\varphi_i = 180°$. The BRDF is recorded in the plane of incidence. The gloss value accessed with a glossmeter varies from 4 gu (full matt) to 95 gu (high gloss). Cut of the specular peaks are reported Figure 2.

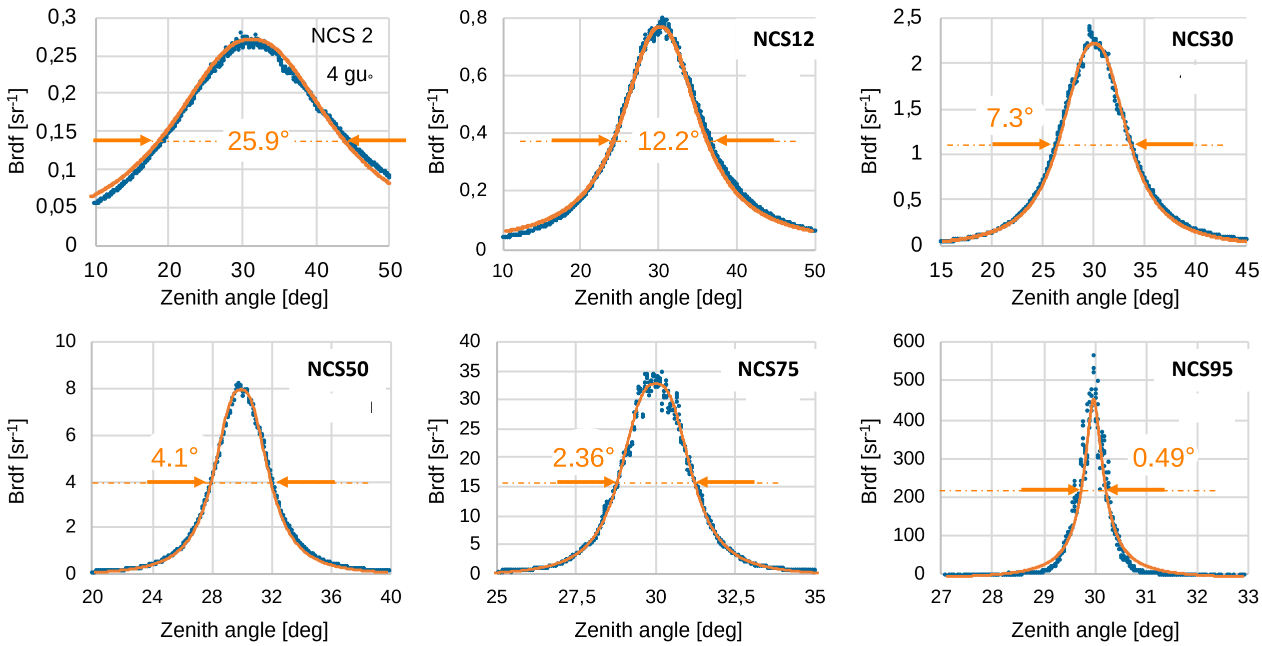
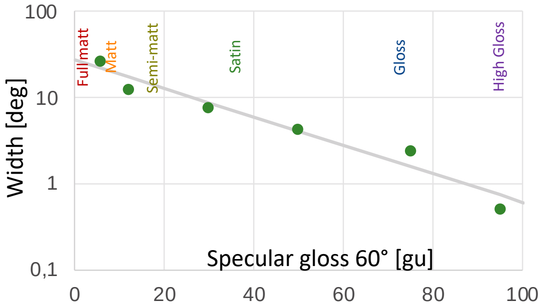


Figure 2. Cut of the specular peak in the plane of incidence for the 6 samples of NCS black gloss scale. Name of samples is on the graphs as well as the specular gloss value. Zenith of incidence is 30°. Peaks are modelled by a Lorentzian function (orange) in order to compute the FWHM reported on the graphs.

From these measurements, the value of the BRDF in the specular direction and the full width at half maximum is computed using Lorentzian model for the interpolation.

If it is assumed that, in order to keep an error below 5 % in the measurement of the width of the peak, it must have an angular resolution at least 20 times smaller than the real width of the peak, then it is possible to provide recommendations on the solid angle of detection. This recommendation can be extracted from an exponential model adjusted on the data. Results are summarised in Figure 3.



	Specular Gloss $_{60°}$ [gu]	Min Peak width [deg]	Max ½ angle [deg]
Full Matt	< 5	22,7	1,5
Matt	5 < G < 10	18,8	1,0
Semi-matt	10 < G < 20	12,8	0,66
Satin	20 < G < 55	3,4	0,15
Gloss	55 < G < 90	0,9	0,05
High Gloss	G > 90	0,6	0,03

Error 5%

Figure 3. Left, evolution of the width of the peak according to the specular gloss 60° that is modelled with an exponential law. Right, recommended angular resolution are allowing a measurement error below 5 % for each category of samples.

More details about this work can be found in the following paper

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 Quadriennal Session of CIE, CIE x046:2019, OP88 (link here)

4.1.3 Impact of using non-infinitesimal spectral and angular bandwidths for BRDF measurements of goniochromatic surfaces,

The spectral BRDF is a key quantity to describe the goniochromatism of iridescent surfaces, as those with special effect coatings which are widely used in automotive, cosmetic or packaging sectors, among others. The spectral BRDF of goniochromatic surfaces changes in great extent for different combinations of illumination and viewing directions (geometries), and it makes their colorimetric description complex. Most of the research work on the appearance of goniochromatic surfaces has dealt with the proper methodology to describe their color by selecting adequate geometries, and to use measurements for representing such surfaces. However, the metrological aspect of measuring the spectral BRDF and the color with real instruments, which have finite-size apertures, has not been systematically studied yet as in this work. Since the appearance of goniochromatic surfaces notably depends on both spectral and angular variables, the non-infinitesimal measurement spectral bandwidth and the non-infinitesimal size of the measurement collection solid angles introduce a deviation from the correct value, and it might be non-negligible in some measuring systems. Moreover, there is an interrelation between these non-finite-size effects. The non-infinitesimal solid angles impact not only on the measured angular distribution but affect also the measured spectral distribution. And vice-versa, the non-infinitesimal spectral bandwidth affects not only on the measured spectral distribution but also on the measured angular distribution. The proper understanding of the uncertainty caused by this interdependence is not only important for a good measurement, but also to improve the design of multiangle- or gonio-spectrophotometers devoted to control the appearance of iridescent surfaces. The objective of this work done by CSIC was to develop a methodology relating the spectral bandwidth and the collection solid angles with the resulting measurement uncertainty, and to provide guidance on the suitable or upper limit values of these variables.

The impact of using non-infinitesimal spectral and angular bandwidths was assessed by the project for BRDF measurements of goniochromatic surfaces, considering a set of interference-based and diffraction-based coatings. From these measurements, it could be concluded that instrument designers should pay attention to the balance between spectral and angular bandwidths when optimising the signal to noise ratio, because their impact on the measurement is not equivalent. From the analysis, recommendations could be given for the measurements of goniochromatic samples (see Table 1). For a similar uncertainty value, spectral and angular bandwidth requirements are stricter for diffraction-based coatings than for interference-based ones. Indicators based on the 95th percentile of the BRDF error or of the colour difference have been defined to establish criteria and recommendations on the thresholds for variables of influence on the measurement of BRDF or colour and have been transmitted to CIE TC2-85.

For more detail, please read the article “Angular and Spectral Bandwidth Considerations in BRDF Measurements of Interference and Diffraction-Based Coatings” (doi:10.3390/coatings10111128) (see here).

Recommended Angular/Spectral Bandwidths	Target Relative Uncertainty (k = 2)
Goniochromatism Based on Interference Pigments	
≤4°/3 nm	<0.5%
≤5°/7 nm	<1%
≤6°/11 nm	<2%
≤6°/17 nm	<3%
Goniochromatism based on diffraction pigments	
≤2°/3 nm	<1%
≤3°/5 nm	<2%
≤3°/11 nm	<3%

Table 1. Recommendations on spectral and angular bandwidths for measuring the spectral BRDF of goniochromatic coating based on interference and diffraction pigments

4.1.4 Effect of the shape of the illuminated area

As already mentioned, the BRDF is defined as the ratio of the radiance in a given direction $\mathbf{R}(\theta_R,\varphi_R)$ by the irradiance along a given direction $\mathbf{I}(\theta_I,\varphi_I)$. Radiance and irradiance are infinitesimal quantities, that means they are defined for infinitely small surfaces. In practice, it is necessary to put light in the setup. Infinitesimal surfaces become regular surfaces that are defined by the user. But in order to get a "correct" BRDF measurement, the illuminated surface have to be chosen "small enough" to guaranty that the variation of the BRDF is negligible within these surfaces. What means "small enough" in practice? The answer depends mainly on the sensitivity of the BRDF to the variation of these parameters.

To put numerical values on these "small enough", CNAM tested the influence of the size and of the shape of measurement area on the three glossiest samples of the commercial gloss scale provided by NCS. These samples were made of inked paper. Their appearance is isotropic and homogenous. The assumption is that there should be no local variation of the BRDF when measurement surface varies. The 60° specular gloss of these samples are 50 GU, 75 GU and 95 GU. Measurements avec been done with ConDOR.

For the study on the size of the measurement area, CNAM used circular field with a diameter varying from 10 mm to 4 mm with a step of 2 mm for each sample. The angular resolution of the measurement is 0.7°. For the study on the shape of the measurement area, the project used different motifs that are all included in a 10 mm diameter circular field diaphragm. Three shapes have been tested: a disk, a ring and a cross (Figure 4). Incident flux is kept at the same level whatever is the shape, in order to avoid linearity and straylight corrections. The angular resolution for this experiment was 0.14°.

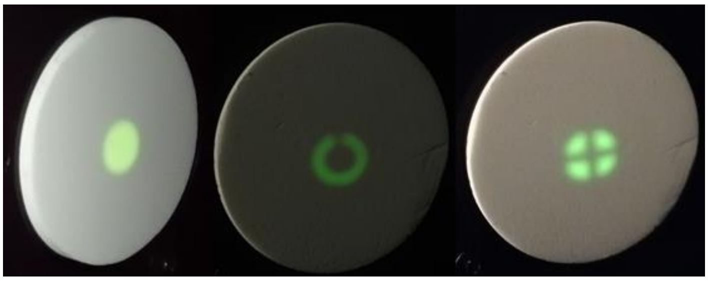


Figure 4. The different shapes of the measurement area tested in this experiment. A disk (left), a ring (middle) and a cross (right). Incident flux is kept at the same level whatever is the shape.

For the three samples, and for the seven shapes and sizes of the measurements area, the BRDF have been measured for one direction of illumination $\mathbf{I}(\theta_I,\varphi_I)$, with θ_I= 30° and φ_I = 0°. The full specular peak was recorded and studied.

For the variation of the size, results showed that the specular peak does not change when the size of the illumination area varies from 10 mm to 4 mm, whatever the gloss of the sample is. However, this conclusion might not be valid for smaller beams and higher angular resolution. Further investigations on this topic will be carried out by EMPIR JRP 18SIB03 BxDiff project to reach submillimetre illumination sizes and to observe the behaviour of the BRDF.

For the variation of the shape, results showed that the specular peak does not change when the shape of the illumination area varies, except for high gloss samples (specular gloss at 60° higher than 90 GU). No clear explanation could be formulated at the moment to explain this behaviour.

This work has been published in AIC proceedings and received the Robert W G Hunt Poster Awards (sponsored by the Colour Group (Great Britain)) :

Rabal A., Ged G., Richard A., Obein, 2020, "Effect of the size and shape of the measurement area on BRDF measurements on glossy samples", *Proceedings of the International Colour Association (AIC) Conference 2020*, Avignon, Nov 2020, pp 384-388 (link)

4.1.5 Influence of the polarisation in goniospectrophotometry

Despite being an important quantity for the characterisation of light, the polarisation state is often not considered explicitly in BRDF measurements. However, almost every apparatus used for reflectometry contains polarisation-sensitive components such as dispersive elements. Therefore, it is crucial to consider the influence of polarisation at least when setting up uncertainty budgets. Polarisation effects have been studied by PTB, CI and CSIC for commonly used sample types in different bidirectional geometries and for several wavelengths. The results were difficult to generalise because the influence of polarisation strongly depends on these parameters. Only the most important findings will be discussed.

Being close to the regular reflection situation, for gloss standards in specular geometry, the reflected light is highly polarised. The s-component (perpendicular to the scattering plane) is up to three times larger than the p-component (parallel to the scattering plane). A degree of polarisation of up to 50 % was observed. This behaviour can be explained by Fresnel-type reflection. For glossy samples in non-specular geometries, the situation is reversed: the radiance factor for s-polarised light is smaller than for p-polarised light. The ratio is independent of the detection angle and the total reflectance. A model has been developed that describes this behaviour and allows fitting of the data (link).

For matte, quasi-Lambertian white reflectance standards in general, the difference in reflectance for s- and p-polarisation increases with increasing illumination or detection angle while the other angle is kept fixed at 0°. The latter angle was chosen to account for standard geometries like 45° / 0° or its inversion. The magnitude strongly depends on the sample material and surface finish. For primed barium sulphate or sintered polytetrafluoroethylene (PTFE) the effect is small, while it can reach non-negligible values for matte opal glass (up to 10 % degree of polarisation).

The situation became more complicated for matte coloured reflection standards. Again, the difference in reflectance grows with increasing angle. It was found that the effect is largest when the value of the total reflectance is small and decreases with increasing value of total reflectance. In some cases, the spectral radiance factor for the p-component is larger than for the s-component. This behaviour cannot be explained by Fresnel-type reflection. A microfacet-based model has been developed which describes the origin of this behaviour. An example of data is shown in Figure 5 and more details can be found in the following paper

T. Quast, A. Schirmacher, K. -O. Hauer, A. Koo; Polarization properties and microfacet-based modelling of white, grey and coloured matte diffuse reflection standards. IOP Conf. Series: Journal of Physics Conf. Series **972** (2018) 012024 (link).

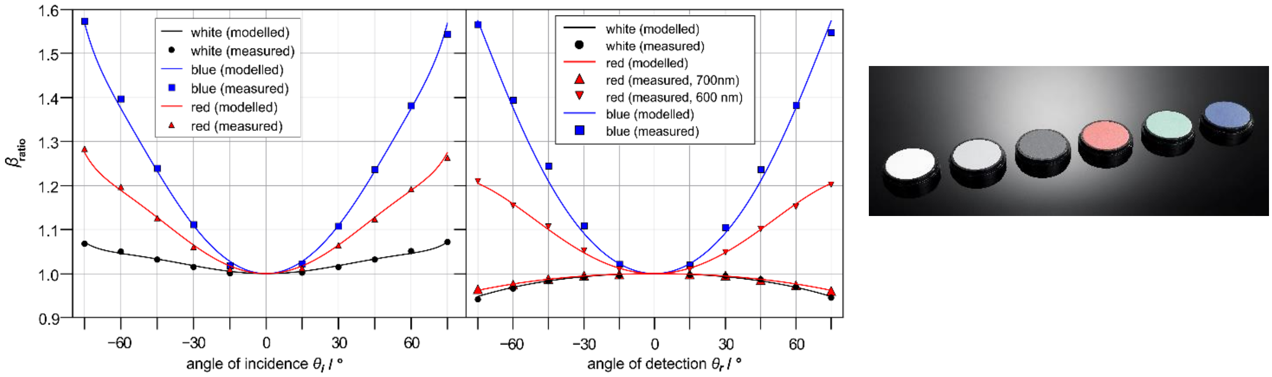


Figure 5. Polarisation-dependent reflectance data for coloured matte ceramic standards. The microfacet-based fit model shows good agreement with the measured data (left: X° / 0°; middle: 0° / X°). Photograph of the ceramic standards (right).

Goniochromatic reflectance samples showed a very complex reflectance behaviour in which the observed colour changes with bidirectional geometry. Regular reflectance, interference or diffraction are involved and make the reflection process prone to be influenced by polarisation. Indeed, large wavelength dependent effects were found. When studying samples based on different effect pigments in the same geometry and at the same wavelengths the situation can be met, that for one sample, the reflectance for s-polarisation is larger than for p-polarisation, while the reverse can be found for the other sample.

In goniospectrophotometry and especially when measuring effect pigments, the required sampling space in terms of wavelength and geometry can easily become very large. Expanding it further by full polarisation measurements can make the determination of the reflection characteristics a tedious task. Therefore, it is helpful, to identify the main contributions, which is in the vast majority of cases the linear polarisation component M/I describing the s- and p- polarisation dependence and derive an estimate for its influence on the final result, the spectral radiance factor or BRDF value. So, in some situations, polarisation effects can be simply accounted for by contributions to the uncertainty budget.

To avoid large uncertainties due to polarisation, a detailed methodology has been presented by CSIC which describes how to assess and correct for the influence of polarisation. It is shown that a thorough analysis of the polarisation properties of the measurement apparatus is required. Depending on the specific set-up and the measurement task, simplified procedures can be derived. An example was presented in a 'polarisation session' of the CIE tutorial on measurement of advanced BRDF. The full methodology is published in Metrologia (here)

To summarise, the project successfully achieved the objective by the successful evaluation of polarization effects in BRDF measurements and by the evaluation of the effect of the solid angles, the sampling steps, the size of the measured area and the spectral bandwidth on BRDF measurements, according to the type of visual effect (gloss, goniochromatic, etc).

4.2 Objective 2: BRDF data handling and processing

4.2.1 Review of existing commercial colour management software for colour quality control of surface appearance

Spectral and photometric BRDF data seems a Big Data challenge at different levels of visual appearance for materials (colour, gloss and texture). Therefore, to unify criteria and to work in a simple way a universal BRDF format is needed to be agreed by consensus of different BRDF communities: from metrologists, spectrophotometer manufacturers and academics working on BRDF models to final user such as developers of Virtual Reality and (3D) videogames or automotive, coatings, architecture, pulp & paper or 3D printers sectors, etc. This universal format guarantees the development of new instruments for better appearance control of real and/or virtual products, to increase the competitiveness of EU industries and to promote the confidence of end-users from the project & CIE recommendations. In this sense, the first step was to evaluate the appearance descriptors obtained from BRDF data and different visualisation modes providing by commercial software. Thus, UA and Aalto made a review on existing commercial colour management software for colour quality control of surface appearance was done. A set of BRDF file formats used in commercial devices (multi-angle spectrophotometers, gonio-spectrophotometers, etc.) and theoretical models was collected from industrial stakeholders, rendering software designers, and international standards (ASTM, CIE, etc.).

In particular, the most used commercial colour management software are ColorCARE® from BASF Coatings, Smart-lab® from BYK-Gardner, CI-Navigator® from Office Colour Science Co. LTD. A brief description is shown below. The ColorCARE® toolbox is a colorimetric software for the organisation, evaluation, and graphical representation of colour and texture data and allows the automation of customer-specific measurement processes. The ColorCARE® toolbox is used in industries where the objective evaluation of colours and textures is very important. The main advantage of this software is that it is compatible with all standard colorimeters used in the automotive industry, therefore it is available to read any file format, thus it has different ways to export data to as well as import data from other applications. Smart-lab Colour belongs to BYK-Gardner, therefore it is used to manage data from BYK instruments, such as the BYK-mac i multi-angle spectrophotometer. Thus, it analyses all data measured with the BYK-mac i: 6-angle colour, sparkle and graininess. The measurements are taken in an online mode and are instantly displayed after measurement. It is possible to visualise the data in different graphics and tables modes (scatter plot, line/travel diagram and spectral curves). In addition, a list of measurement conditions (illuminant observer, etc) is available together the option of different equations to compute or apply colour tolerances. CI-Navigator is a software developed mainly for the purpose of managing metallic and pearlescent colour samples. This software works with any multi-angle spectrophotometer and an imaging device. CI-Navigator provides a variety of graphs to apply the colour quality control. In addition, it is easy to compare and evaluate a trial colour with a target colour from different viewpoints. The main point of this software is that calculates the precise formula based on both spectral reflectance measured with multi-angle spectrophotometer and image data, therefore it can agree not only colour but also sparkle and graininess with the target colour's at a visibility level. Furthermore, CI-Navigator can provide realistic Computer Graphics while changing background and /or illumination. Therefore, it is useful to estimate not only colour itself but also colour design of the product.

Different visualisation modes from BRDF data were found in the literature and commercial software: spectral, XYZ and angular representations, CIELAB colour space representation (aspecular and interference lines), colour travel, colour differences and tolerances and colour palette in sRGB colour space. In this sense, different discussions between stakeholders and the project were carried out to identify the elements to be included in the universal BRDF file format to be able to obtain enough information about the appearance descriptors. From a survey, and after discussion in progress meetings, a datafile format was agreed by the project and stakeholders. The JSON format was selected because it is more readable than *xml* format and allows simply return field "metadata" from file without the need of additional parsing. The decision was reported to CIE TC2-85 and CIE TC4-50. The project tested the proposal of using JSON format for one year and proposed ameliorations. The final version can be consulted here.

4.2.2 Universal BRDF file format in JSON

Single BRDF data point is a ratio of directional radiance and directional irradiance recorded at four different angular coordinates. Meaning that in most classic and general form, full BRDF data is a set of points in 5D space where one dimension corresponds to value of the ratio, two describe illumination angular conditions and two indicate viewing angular conditions. It might seem ordinary at a first glance, but from the point of view of data storage this presents some challenges.

First, data with dimensions above 3D can't be directly mapped to 2D array (3rd dimension is a value) and hence can't be easily saved as a table (comma/tab separated values) or spreadsheet. To get around this issue, one needs to beforehand define three principal dimension variables among which data is grouped into 3D chunks and then mapped to 2D arrays that are afterwards stacked one after another in the chosen order corresponding to remaining non-principal variables. For 5D BRDF data a ratio of directional radiance and directional irradiance or simply BRDF value is usually chosen as one of the main principal dimensions while other four are equally valid choices for remaining principal dimensions. That reveals the second problem.

There are many ways to choose principal dimensions and hence differently structure BRDF data. In fact, the choice is often governed by BRDF measurement methods and instruments, which algorithms favor data acquisition and saving in specific order. This limits comparability of different BRDF data sets as introduces a need for additional data interconversion that might not be available in commercial software or requires additional effort from researchers to modify internal processing programs.

Third, for most modern applications 5D BRDF data is not sufficient. Many laboratories are interested in spectral BRDF data to have information about color properties of the samples. Other laboratories observe BRDF dependance on illumination polarisation and hence in some cases polarisation is varied during BRDF measurements. As a result, the dimensionality of the BRDF data expands and even more options for choosing principal dimensions emerge.

To tackle presented problems, the project took first steps in standardisation of BRDF data. Partners proposed a universal BRDF file format that could be used by stakeholders in the entire industry for streamlined storing, exchange and comparison of BRDF data.

Minor restrictions were imposed for this task. It was agreed that BRDF file format should be preferably text based, simple, sensible, human readable, easy conversion, and easily parsable by common programs.

Several iterations led to the decision to adapt JSON text format for the needs of BRDF data. This prevented the complex process of development and integration of completely new text format and resolved most of imposed restrictions. Since JSON is very simple and well-established file format, the majority of modern software used in research such as Matlab, Origin Lab, Microsoft Office etc. already support it and easily parse JSON files. Availability of different online and offline JSON data readers makes files easily readable for humans. Moreover, many programming languages including C, C++, C#, Java, JavaScript, R, and Python, have built in easily available libraries for processing JSON and almost no effort is needed to start work with the data. This also enables an uncomplicated conversion of other files into JSON. There are available ready converters for common file formats such as csv, tsv, xml etc. and it is not difficult to develop a custom convertor for specialised data files produced by commercially available equipment.

BRDF file format is based on JSON syntax that is a text file that stores data in dictionaries in the form of: `{key: value}` where key is 'string' type and value can be 'string', 'number', 'array', 'True', 'False', 'Null' or 'object' i.e. another '{key: value}' structure (Figure 6).

The project agreed on following keys and structure in the BRDF file format:

```
{
 head:{                        # Header section. Has quite loose definition. Keys and contents may vary freely, but
                               # must follow json syntax and data types.

       date: "dd-mm-yyyy",     # Value --> String. Date format is fixed as shown here.

       any key: any data       # For example, detection slid angle, list of authors, institute or organization where
                               # measurements were made etc.
     },

 data:{                                   # Data section has a strict definition. All keys should remain as
                                          # specified and adding other keys is not allowed.

       #=================================== Illumination properties keys ======================================

       #----------------------------------- Primary axis --------------------------------------------------

       wavelengths: [λ1, λ2, ..., λN],      # Value --> array of numbers. Primary axis or row vector for data.
                                          # Wavelengths at which each data row was measured.

       #----------------------------------- Non-primary axes ----------------------------------------------

       pol: [pol1, pol2, ..., polM],      # Value --> array of strings. Names can be any  - i.e. 'p','s' or
                                          # 'p-polarized', 's-polarized' or any other would be read correctly.
                                          # NB! If you have two or more different values for polarization,
                                          # parser will automatically calculate average of all of them.
                                          # this feature is cannot be disabled at the moment, but it doesn't
                                          # disturb BRDF viewing in any scenario. If you used unpolarized light,
                                          # insert 'u' or 'unpolarized' respectively.

       theta_i: [θi1, θi2, ..., θiM],     # Value --> array of numbers. Illumination incidence zenith angle.
                                          # Can vary +/-90 deg around normal to the sample.

       phi_i: [Φi1, Φi2, ..., ΦiM],       # Value --> array of numbers. Illumination incidence azimuthal angle.
                                          # Can vary 0 to 360 deg. Depends on measurement procedure.
                                          # If theta_i is measured only from 0 to 90, then it is wise to use
                                          # range 0 to 360 deg.
                                          # If theta_i is measured +/-90 around normal, i.e. you measure
                                          # simultaneously data at theta_i and theta_i + 180,
                                          # then it is better to use range 0 to 180 deg to avoid data overlapping.

       #=================================== Viewing properties keys =========================================

       #----------------------------------- Non-primary axes ----------------------------------------------

       theta_v: [θv1, θv2, ..., θvM],     # Value --> array of numbers. Illumination viewing zenith angle.
                                          # Can vary +/-90 deg around normal to the sample.

       phi_v: [Φv1, Φv2, ..., ΦvM],       # Value --> array of numbers. Illumination viewing azimuthal angle.
                                          # Can vary 0 to 360 deg. Depends on measurement procedure.
                                          # If theta_i is measured only from 0 to 90, then it is wise to use range
                                          # 0 to 360 deg. If theta_i is measured +/-90 around normal, i.e. you
                                          # measure simultaneously data at theta_v and theta_v + 180,
                                          # then it is better to use range 0 to 180 deg to avoid data overlapping.
                                          #
                                          # NB! In current version, the projection heatmap polar plot won't operate
                                          # correctly if ou measured twice one and the same plane. It is common if
                                          # you have measured BRDF at phi_v = 0 in the beginning of measurement and
                                          # 180 or 360 in the end of the measurement depending if theta_v varies
                                          # from +/-90 or 0 to 90 around normal).
                                          # Try to avoid this by manually selecting which of two datasets in
                                          # the same plane to leave in the file.
                                          # If you would like to test repeatability by measuring multiple data
                                          # sets in one plane, try to separate data to different file int present
                                          # format. That way you would be able to analyze them while seeing all
                                          # graphs correctly.

       #=================================== Data points =====================================================

       data: [[point1, point2, ..., pointM], # 1    # Value --> array of arrays of numbers.
              [point1, point2, ..., pointM], # 2    # 2D array of measured BRDF values corresponding to illumination
              ...,                                  # and viewing properties defined above. There are N rows
              [point1, point2, ..., pointM]] # N    # corresponding to the number of values in primary axis, i.e.
                                                    # number of wavelengths. Each row contains an array with the length
                                                    # of M corresponding to the number of values in all non-primary axes.
  }
}
```

Figure 6. Keys and structure in the BRDF file format

Files can have extensions such as .json or .brdf. For example (toggle code/tree options to study the file) Example 1, Example 2).,

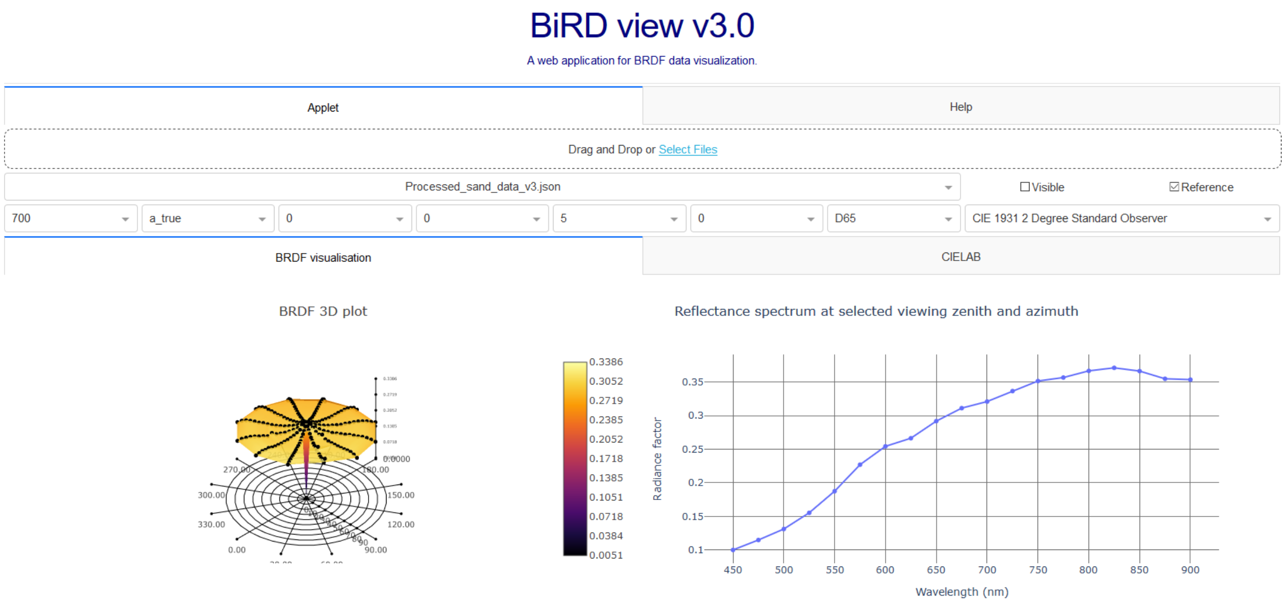
4.2.3 BiRDview, the open-source app to visualise BRDF measurements, colour travel, digital RGB, and more

Classical appearance descriptors used in academy or industry e.g. polar mode, colour travel, digital RGB visualisation, etc. were collected and reviewed. The information was presented and discussed with the project's stakeholders at a progress meeting. From this discussion, an open-source code named BiRDview was generated by Aalto; its main function is to show BRDF measurements from different equipment. BiRDview is an open source web-application. The application is written in Python using Plotly Dash open source library and the code can be found here. The current version of the application allows to open and view files only in the file format developed and agreed by the project.

It has the following features:

- An **Applet** and **Help** tabs that allow to toggle between main applet screen and a help page with information about file format as well as quick guide about how to use the application.
- An **upload field** where files can be either dragged and dropped or to open a file selection dialogue to choose files to be opened. Uploading of multiple files is allowed and "loading" animation will be shown until all files are loaded. Uploaded file's/files' name will appear in the dropdown menu below the upload field. In the current version, the uploading of files with the same name is also allowed. This allows to compare data from one and the same file with itself when it is needed.

- ➢ An **uploaded file selector** that allow to select one of the uploaded files as an active by clicking a dropdown menu with file names and to select a file by clicking on its file name. After that, a menu with the file parameters as well as figures will be updated for the corresponding file.
- ➢ A **menu bar** where file parameters can be selected. By definition BRDF data has more than 3 dimensions that makes it impossible to depict all the data on a single figure. For this reason, smaller pieces of data should be selected and depicted on multiple figures. In BiRDview this can be performed by using dropdown menus located under file selection dropdown. There are selections such as: wavelength, polarisation, incidence zenith angle, incidence azimuthal angle, viewing zenith angle, and viewing azimuthal angle (from left to right). There are also two options related to colour analysis allowing the selection of Illuminant and Observer to estimate CIELAB values.
- ➢ Four **BRDF data graphs** (Figure 7)**.** First - top left - provides the 3D shape of BRDF at specified wavelength, polarisation, incidence zenith and azimuthal angles. Changing these parameters will cause the figure to update. Dots on the figure represent measured data points and by hovering the mouse over them one can see measured values. Colour coded surface drawn though measured points gives an idea about the shape of the BRDF. Bottom left figure represents the projection of 3D plot to the XY plane and converted to the polar plot. By rotating plot one can select viewing azimuthal angle in parallel with corresponding dropdown menu. This selects a plane for 2D BRDF plot located on the right (bottom-right). 2D BRDF plot shows the BRDF at specified wavelength, polarisation, incidence zenith, azimuthal angles and selected viewing azimuthal angle. Changing these parameters will cause the graph to be updated. By clicking on a point on this graph it can be seen the reflectance spectrum at this point. BRDF spectrum at specified polarisation, incidence zenith, azimuthal angles and selected viewing azimuthal and zenith angles is depicted in top right figure. It gives an idea whether the measured sample changes its colour under different illumination and/or viewing circumstances or not. This spectrum is used for further colour and CIELAB values calculations.



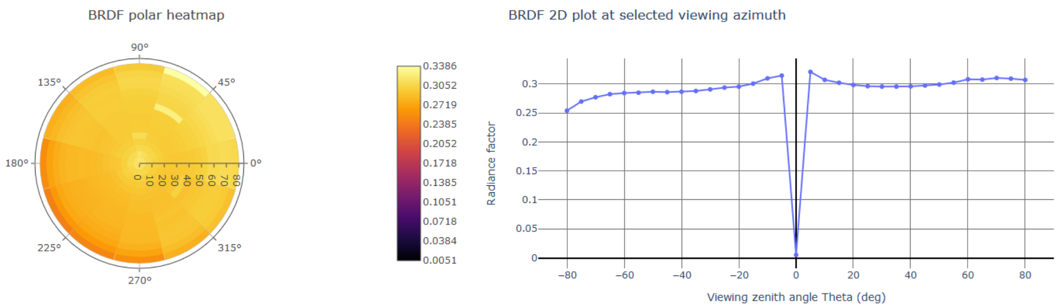


Figure 7. Screenshot of BiRDView when processing a BRDF data file. BRDF is here visualised in 3D shape (top left), in polar plot (bottom left) or in a cut along a selected azimuth angle (bottom right). Reflectance spectrum can be plot for a selected angular configuration (top right). Other visual tools (polarisation, incidence zenith angle, incidence azimuthal angle, viewing zenith angle, and viewing azimuthal angle) are available.

- **Simultaneous view of data from different files.** To view and compare data of a selected file with some other file that will be selected in the future, it is necessary to place a check mark in the checkbox named "visible" in the dropdown on the right. In this case, when other file is selected, data from the file marked as visible will appear on the 2D BRDF and BRDF spectrum plots. This feature is disabled for 3D and projection figures since it will disturb analysis rather than help it while slowing down the app.
- **Interactive figures.** BiRDview app uses plotly graphing library that allows to create quite interactive figures. The app allows to move graphs, rotate them, zoom to specific areas, get information by hovering mouse over data points and much more.

There are also tabs to toggle between BRDF visualisation and CIELAB colour visualisation mode. The latter is under development and its features will be revealed in the future in additional text and guide under Help tab as well all further features that will be developed by community in the future.

Currently program is actively used by Aalto for visualisation and analysis of BRDF data of the sand measured during project EMPIR 16ENV03 MetEOC3.

To summarise, the project successfully achieved the objective by proposing a universal file format for BRDF measurement and an easy to use open access visualization application.

4.3 Objective 3: Gloss measurement and visual perception

4.3.1 State of the art on gloss measurement and gloss perception and bibliographic database

Understanding material perception and the visual assessment of material properties such as glossiness, roughness or translucency, has received increased attention throughout the past 15 years. With respect to surface gloss perception, latest research has primarily focussed on investigating the influence of, and the interactions between illumination, surface properties, and observer.

A CIE reportership was established in response to these new studies and provided insights, with the purpose to draw up a database of key research articles and terminology related to gloss perception and gloss measurement, and to investigate if, from this database, opportunities or guidelines for optical characterisation of surface gloss in a closer agreement with the human visual perception of surface gloss may be proposed.

A database consisting out of 69 research papers about gloss measurement and gloss perception was established by KU Leuven, CNAM and Innventia. Stress was laid on work published over the past 15 years. Yet, key research contributions on the standardisation of surface gloss measurement and on gloss perception, published earlier, were also taken into account.

Specific terminology related to gloss, found across the consulted research papers, was summarised in a glossary of terms, after first being checked that it is defined in an ISO standard. 30 items were finally retained and presented together with their definition(s) and reference to the defining standard(s) in a separate document. All documents are accessible on the project website (here)

Overall, research findings corroborate a multidimensional account of the perception of surface gloss. Instead of approximating the physical dimensions of surface reflectance, the visual system seems to analyse and to rely on available diagnostic cues when making a perceptual judgement of relative gloss. Although the exact mechanism of gloss perception remains unknown, it was therefore envisaged, from a metrological point of view, to investigate if a standard observer of individual quantitative scales of reported visual cues to glossiness, as they are psychophysically experienced under typical circumstances, could be defined. Indeed, while it has been proven to be complicated to determine the overall gloss impression of a surface as a single quantity, it is probable that each single diagnostic (image) cue (distinctness of the highlight, contrast, size, etc.) could be quantified more accurately. What the dedicated sets of specimen and the appropriate assessment conditions (type of illumination, illuminance level, viewing distance, etc.) are that should be used for the development of such new psychophysical scales, remains however to be determined. This conclusion supported the need for further collaborative research, which could be accelerated and accommodated within a new Technical Committee (TC) on the subject (see activity 4.3.2).

4.3.2 Launch on a new CIE Joint Technical Committee on gloss

In May 2018, KU Leuven submitted a proposal on the creation of a Technical Committee on gloss to CIE Division 1. After discussion, the creation of CIE JTC 17 with the title "*Gloss measurement and gloss perception: A framework for the definition and standardisation of visual cues to gloss*" has been approved by CIE Board of Administration. This technical committee is a transversal committee between Div1 (Colour and vision), Div2 (Measurement of light and radiation) and Div8 (Image technology).. The term of reference is to describe recommendations for standardised visual assessment conditions of individual, established cues to gloss, to make recommendations for the definition of a standard gloss observer for individual diagnostic cues and, based on the findings from the above, to suggest optical methods and metrics for describing gloss in correlation with the established gloss cues.

The establishment of the JTC has been strongly influenced and supported by the project. The JTC had his kick-off meeting in Oct 2018 at CSIC in Madrid, during the Workshop entitled "Open questions on gloss measurement", organised by the project. After collection of data provided by the different teams implicated in the JTC, a first draft for the JTC recommendation has been submitted by JTC chair to members for review on Feb 2021, few months after the end of the project.

4.3.3 Development of a new measuring equipment devoted to the measurement of gloss

Imaging systems are getting used more and more frequently today as measuring systems in various branches of industry. Compared to non-imaging systems, they allow various forms of image analysis to be applied through post-processing.

KU Leuven investigated the potential use of imaging systems for surface gloss analysis by developing a camera-based prototype according to the specifications of the optical layout of a specular gloss meter in a 60° measurement geometry, as described in ASTM D523-14 (Figure 8). The photodiode detector was thereby substituted with a CMOS detector. The optical layout of the system was designed and validated by the use of raytracing software.

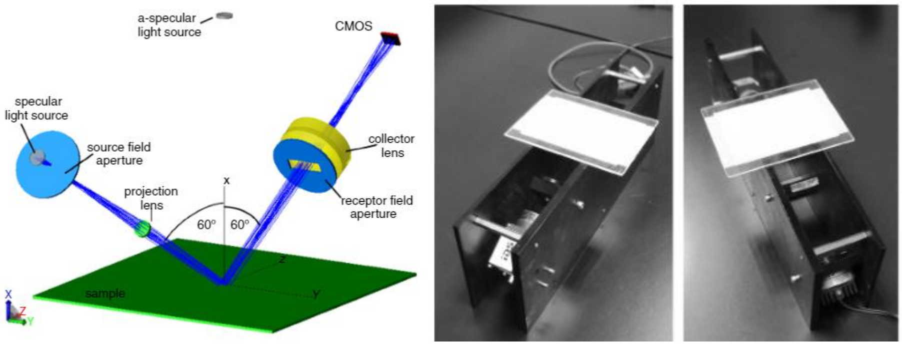


Figure 8. New measuring equipment devoted to the measurement of gloss. Left, raytracing simulation of the measurement done in agreement with ASTM D523-14. Left, the prototype instrument, where the photodiode is replaced by a CMOS detector

A series of 16 matte to high-gloss test samples, with nominal gloss values ranging between 3 and 90 gloss units, was used to compare specular gloss measurements obtained with the developed prototype instrument and a commercial specular gloss meter. An average and maximum deviation of only 1.2 and 2.7 gloss units, respectively, was thereby obtained, confirming the suitability of the system to perform standard specular gloss measurements.

The potential benefits of the image-based approach were then studied further. By way of example, the optical characterisation of orange peel and contrast gloss by use of the system was discussed, corroborating the fact that the proposed instrument offers important opportunities for a more global characterisation of the total gloss impression.

This work has been published under the following reference and can be found here:

F. Leloup , J. Audenaert, P. Hanselaer (2019), "Development of an image-based gloss measurement instrument", *J. Coat. Technol. Res.*, **16** (4), 913–921.

4.3.4 Evaluation of the effect of the illumination of the perception of gloss

The visual sensation of gloss is built on cues deduced from the interaction between light, surfaces under evaluation and surrounding conditions. Gloss is a second-order attribute of the visual appearance. This means that its perception is not directly encoded on biological sensors but constructed from the global scene in the field of view of the observer. That's why gloss is a complex quantity to measure. The project aimed:

- to quantify the effect of the nature of illumination on gloss sensation
- to quantify the effect of surrounding conditions on gloss sensation
- to test up to where the concept of gloss constancy, i.e. that fact that the sensation of gloss remains constant whatever are the illumination conditions, according to the gloss level.

To achieve these objectives, CNAM used an unidimensional gloss scale developed by NCS company. The specular gloss at 60° of the scale ranges from 1.8 gu to 93.5 gu, with an expanded uncertainty below 1 gu. Observations were done on real samples, in a real environment. Twenty-nine observers, 14 men and 15 women, took part in the experiments. Two types of illuminations, *specular* and *diffuse* were tested. The *specular* lighting simulates a sunny sky. The *diffuse* lighting simulates a cloudy sky. For both lighting, the photometry is adjusted to provide an illuminance of 1600 lx. Two types of environment, *standard* and *realistic* have been used. The *standard* environment is similar to the one depicted in the ASTM D4449-15 standard. The inside of the light booth is covered in black diffuse curtains. The *realistic* environment mimics an office cubicle (Figure 9). Visual scales have been built using a protocol based on maximum likelihood difference scaling (MLDS) method. This protocol allows to provide values with associated uncertainty.

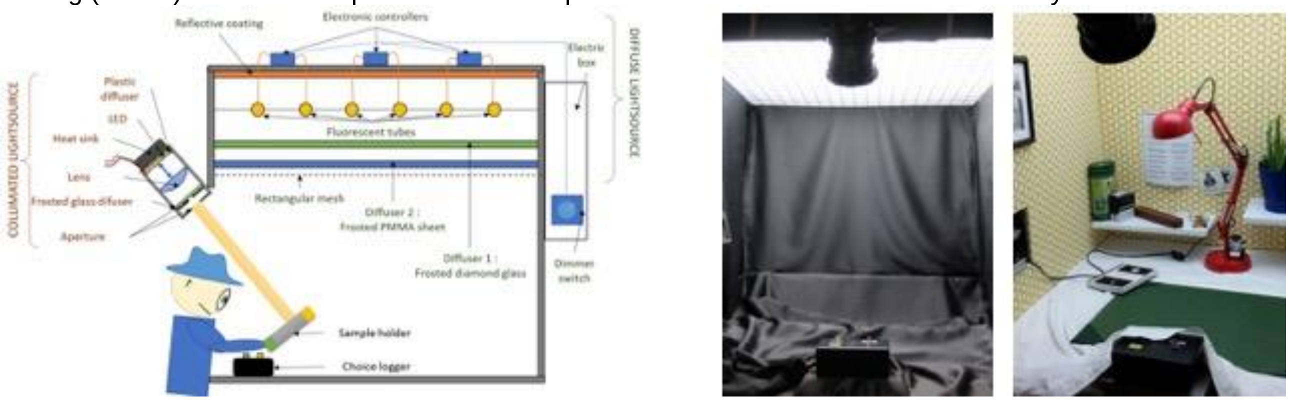


Figure 9. Experimental setup for the visual evaluation. Left, schematic of the light booth, with the fluorescent tubes and diffusers allowing the diffuse lighting and the collimated light source above the head of the observer that simulates the sun for the specular lighting. Right, the standard environment and the realistic environment

Results showed that the visual scales are different when the type of light source used for the measurement changes (Figure 10, left). The lighting mainly affects satin and matt samples (specular gloss below 50gu). For these levels, the visual sensitivity is almost null when doing evaluation under the *diffuse* lighting, while observers keep their ability to rank the samples under the *specular* lighting. It is noticed that the glossmeter is not correlating well with the visual sensation because an inversion in the ranking could be notice for the third sample. For glossy samples (specular gloss above 50 gu), the lighting has no effect and gloss constancy is maintained.

Visual scales are similar when the environment changes (Figure 10 right). Nevertheless, it is noticed that the *realistic* environment increases the visual gloss dynamic. This increase in dynamic could be explained by the presence in the *realistic* environment of supplementary clues that the visual system can interpret. The use of *realistic* environment of evaluation, lit by a *specular* source should be encouraged.

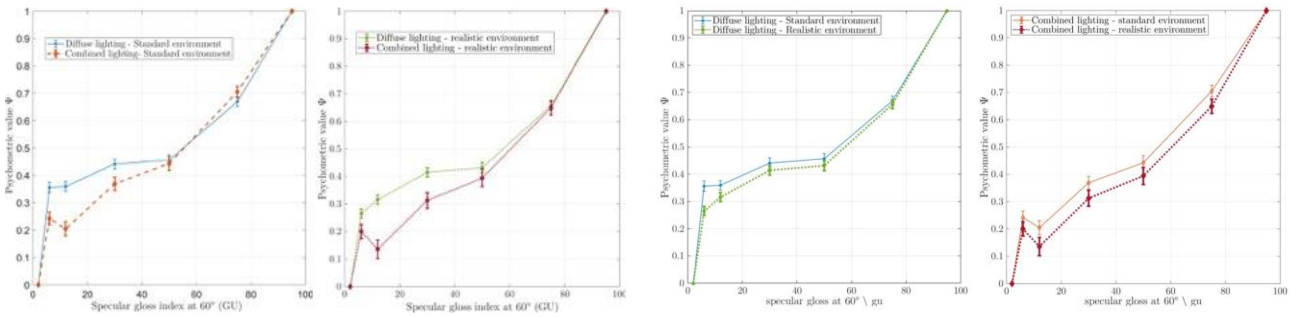


Figure 10. Evolution of the sensation of gloss according to the specular gloss. Left, effect of the lighting (sunny versus cloudy). Right effect of the environment (standard versus realistic)

In conclusion, the visual system tries to maintain gloss constancy in the same way it does for colour. As the perceived colour of an object is kept constant under light sources of different colour temperatures, its glossy appearance is perceived identically despite changes in the lighting divergence. This adaptation is to be associated with the natural variations of illuminations that it can be met in everyday life (colour temperature of the natural light at sunset or at noon and changes of divergence induced by meteorological conditions). Similarly, to colour constancy, the link between gloss and light source can be broken. Considering for instance a *diffuse* lighting over a scene deprived of environmental clues, observers are facing a difficult task. They no longer have a specular reflection to base their judgment particularly for matt samples below 50 gu. As a consequence of that, gloss constancy is lost for these samples. More details are available here.

To summarise, the project successfully achieved the objective by a) the successful evaluation of the evolution of the sensation of gloss under different types of illumination, b) the development of a new generation of glossmeter and c) the creation of a CIE JTC at a global level to normalize a new approach for the quantification of gloss.

4.4 Objective 4: Sparkle measurement and visual perception

4.4.1 Launch on a new CIE Joint Technical Committee on sparkle and graininess

A proposal for the creation of a CIE TC was prepared by CSIC and accepted by CIE. A Joint Technical Committee (JTC 12) was established that involves CIE divisions 1 (Vision and Colour), 2 (Physical Measurement of Light and Radiation) and 8 (Image Technology). This JTC has 21 members. A first draft on sparkle and graininess measurement has been submitted to the JTC for review. It includes a methodology for the spectrophotometric measurements, definitions and concepts regarding contrast threshold, and a physical model which can describe both sparkle and graininess.

Within this project, four articles in peer-review journals (Journal of Modern Optics, Metrologia and two in Optics Express) were published that will provide an important contribution to the work of JTC 12. They will be commented in the following sections. The publication of these articles will allow other research groups to explore the proposed methodology for measuring sparkle and graininess., These independent psychophysical experiments are necessary to validate the proposed scales.

4.4.2 Test of a new sparkle measurement methodology at NMI level

The definition of sparkle and a methodology for its measurement were developed, based on works done in a previous project EMRP JRP IND52 xDReflect. In order to evaluate the capabilities of new sparkle measurement methodology at NMI level, nine achromatic sparkle specimens, produced with different sizes and concentrations of effect pigments, were selected and assessed at three different geometries, with low, medium and high specular angles (defined as the angular distance between the collection and the specular directions).

The measurement of the sparkle quantities was independently carried out by three different national metrology institutes (PTB, METAS, CMI), and one designated institute (CSIC). Each of these NMIs have developed its own setup to perform measurements according to the methodology proposed, meaning that the measuring systems with different light sources, rotation mechanisms for the realisation of angular geometries, and imaging luminance measurement devices were used. Furthermore, each NMI used its own strategy to obtain HDR images by combining acquisitions at different integration times.

Although completely independent measurements of luminance factor images were carried out, exactly the same measuring system-independent algorithm was applied to the measurements to obtain sparkle quantities, sparkle visibility and sparkle density. Therefore, any variations in the results have to be related to the differences in the measuring systems, and not in the scale realisation. The most relevant differences in the measuring systems are mainly geometrical factors, such as the spatial resolution and the irradiation and collection full angles.

To better identify possible systematic biases of the measuring systems, the compatibility of the measurements was studied. Figure 11 shows the compatibility data plotted in a $C(d_S)$ - $C(\mathrm{Q}_{\mathrm{Q2}})$ diagram, where x-axis represents the compatibility index of sparkle density and y-axis the compatibility index of sparkle visibility. The values within the central square represent combinations of sample and geometry whose sparkle density and sparkle visibility measurements are both compatible with the general result. Those measurements only compatible in sparkle density are lying within the vertical -1 and 1 lines, whereas the horizontal -1 and 1 lines enclose those measurements only compatible in sparkle visibility. The incompatible measures in both sparkle density and in sparkle visibility were used to identify two possible sources of systematic errors: inadequate illumination and collection solid angle angles, and inadequate size of the virtual aperture used to assess the luminous flux reflected on the effect pigments. More in depth results can be found here.

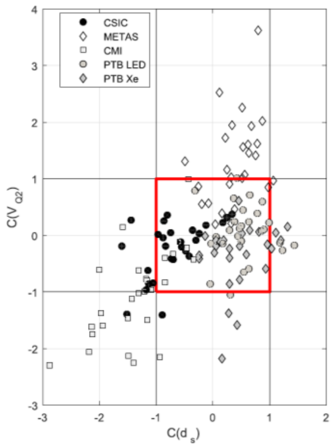


Figure 11. Compatibility data of measurements. The values within the central square represent combinations of sample and geometry whose sparkle density (d_S) and sparkle visibility (V_{Q2}) measures are both compatible with the general result.

4.4.3 Exploration of sparkle as a visual attribute

A full psychophysical study was set up and performed by UA to validate the linearity between the visual sensation of sparkle and the instrumental measurement scale proposed. In this way, a particular selection was made of a relatively small number of items with systematically variations in sparkle attribute. Following this idea, nine samples were selected. These samples are achromatic cards from the "Effect Navigator" catalogue produced by Standox with different concentration particle size of the effect pigment. For sparkle evaluation, the Byko-spectra effect light booth from BYK-Gardner was selected. This light booth includes well-defined directional light sources to enable visual assessments of sparkle. For this experiment, the 45ºas45º measurement geometry was selected. A wLED lamp, slightly colour-filtered with yellowish nuance is implemented with chromatic coordinates equal to x = 0.3415 and y = 0.3821 and a colour temperature of 5208 K and colour rendering index equal to 71.51. To carry out this work, different measurements were obtained through a psychophysical method of triads. This is a method of forced choice, which is characterised to be a method where the question to the observer is clear and simple, and also forces him to make a decision between a limited number of possible options. Each judgment is totally independent of the previous one. For this study, the method establishes a forced choice between two possible alternatives. In each trial, the observer visualises three samples, one in the centre and two on each side. The task of the observer is to select those sample whose attribute to study (sparkle) is most similar to that of the central sample. A total of 84 different comparisons or trials were established for each experiment. These combinations were made at random by combining the 9 selected samples and making non-repetitive combinations of the 9 samples in groups of 3. The presentations followed a pre-established disordered criterion, so that there was no sequence that could be detected by the observer and influence the observer's responses. Each observer performed three repetitions of the same experiment in three different sessions. The sessions lasted approximately 30 minutes to avoid observer fatigue and ensure better response. At the beginning of each session, the observer remained 3 minutes with only the cabinet light on, in order to adapt to the measurement conditions. In total, 252 visual observations were made per observer. Regarding observers, before starting the first session it was checked if they were suitable for the study. Therefore, the visual acuity was measured to guarantee a visual acuity with a Snell test higher or equal to 20/20. In addition, the colour vision of participants was evaluated by Ishihara's test. In this experiment twenty people participated (15 females and 5 males) with an age range between 23 and 58 years, with an average value of 27.8 ± 9.5 years. At the beginning, observers were well instructed regarding the sparkle effect. To explain to observers the corresponding texture effect to be evaluated, a solid sample (without effect pigment) was placed close to a test sample in the corresponding lighting booth. Then, the sparkle effect was introduced as glints or bright dots on a uniform background, similar to the sky perception on the night (stars on a dark background). The designed psychophysical experiment was chosen to be able to apply a multidimensional analysis. Finally, visual data (referred here as visual sparkle) are obtained from the visual experiments. They are relative values and depend on the design of the visual experiments, but their tendency allows conclusions to be drawn on the appearance or on measurement scales. A very high correlation was found between the sparkle quantity (defined in the previous section) and the first dimension of the visual data (visual sparkle) obtained through the visual assessment (linear correlation coefficient r = 0.992) (Figure 12).

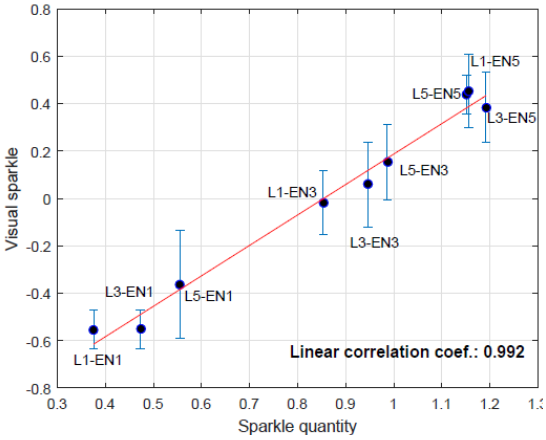


Figure 12. Relation between visual sparkle and the calculated sparkle quantity. The error bars represent the inter-observer standard deviation. Note that the values of visual sparkle only can be interpreted in relative terms, and they can be negative.

4.4.4 New methodology for the measurement of graininess

A methodology was proposed for traceable graininess measurements based on the results obtained for 25 graininess samples with different concentrations and sizes of pigments. The average luminance factor and “graininess variance” were identified as the relevant reflectance-based quantities to measure graininess.

Graininess may be described as spatially-correlated lightness variations on the surface. In order to evaluate the spatial variations at different spatial frequencies, the Power Spectral Density (PSD) was calculated for each graininess sample (see Figure 13). The integration of the PSD between spatial frequencies f_1 and f_2 represents the spatial variation only between those spatial frequencies. This formalism, proposed within this project, allows the measured PSD to be connected with visual data from visual experiments, by determining those values of f_1 and f_2 which provide the best correlation.

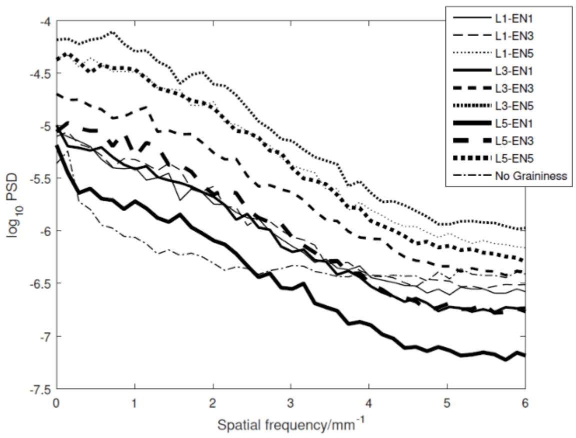


Figure 13. Calculated power spectral density (PSD) for the examined samples. This quantity allows the graininess variance to be calculated, which is correlated with the appearance of graininess.

An equation to relate the reflectance-based quantities and, indirectly, the structural variables with the visual data of graininess has been proposed in the article “Definition of a measurement scale of graininess from reflectance and visual measurements” (doi.org/10.1364/OE.26.030116) (see here) and shared with the Joint Technical Committee JTC 12 “The measurement of sparkle and graininess”. An evaluation of the graininess as visual attribute was made by means of a psychophysical experiment and a multidimensional scaling algorithm, described in the next subsection.

4.4.5 Exploration of graininess as a visual attribute

Different visual experiments were conducted to explore the graininess as visual attribute. Firstly, a study was performed to find how many dimensions are necessary to totally characterise this texture effect. To perform this study, the multidimensional scaling algorithm was considered taking into account the visual perception of observers. As input, the distances or dissimilarity between stimuli has to be computed. In this work, the disparities were calculated through a psychophysical experiment. The advantage of combining this algorithm with a psychophysical experiment is to keep in mind the visual perception of this attribute. The visual experiment to scale the graininess differences was based on the interval method (point rating scaling). The difference was specified on a line: the start point marked 0 and an endpoint marked +++. The starting point (0) means there is no difference between samples. The endpoint (+++) means the difference between samples is very great. The observer indicated the perceived difference of the presented pair on the line by a mark (x). To quantify the perceived difference the distance between the starting point (0) and the observer’s mark (x) was measured. Each observer performed three repetitions after a training session. There were a total of 17 observers in the experiment (11 males and 6 females) with an average age of 33 years old. All the observers participating in the experiment had a best-corrected visual acuity of 1 (decimal scale). The VeriVide viewing booth was used to run the experiment. The selected illuminant was the D65 illuminant. The experiment was conducted in a dark room and the observers spent 3 minutes to adapt to the lightness conditions. A set of 25 samples were selected to run the experiment. The samples belong to the Effect Navigator® chart from

Standox. The selected samples were achromatic samples and they were divided into different groups considering the lightness value. This classification was done to avoid other contributions to the graininess perception. Two different instruments were used to measure the graininess of the samples: the BYK-mac-i multi-angle spectrophotometer and a gonio-hyperspectral imaging system developed in the Centre for Sensors, Instruments and Systems Development (CD6) at the Universitat Politècnica de Catalunya. In this instrument, graininess attribute is defined by specific indices, mainly based on first and second order statistics associated with the co-occurrence matrix. Finally, 10 different pairs were compared for each group. Then, each observer performed 50 visual assessments in a session of 30 minutes to avoid fatigue. Three different sessions were run for each repetition. Finally, the multidimensional analysis was carried out to evaluate the minimum number of dimensions needed to define or characterise the graininess attribute. From this analysis, it can be concluded that two dimensions are involved in the perception of graininess. A relationship between visual and instrumental graininess was evaluated taking into account two different instruments (Figure 14). On one hand, the graininess value (G) provided by the BYK-mac-i instrument was considered. First dimension matches perfectly with the instrumental graininess, while there is no correlation between any variable and the second dimension. On the other hand, the parameters proposed by the gonio-hyperspectral system were considered focused on first and second order statistics. It is found a good relationship between the first dimension and the correlation parameter, defined as the digital-level linear dependencies in the image. The other parameters were also considered to give a meaning to the second dimension. However, there was no correlation with any feature associated with the co-occurrence matrix.

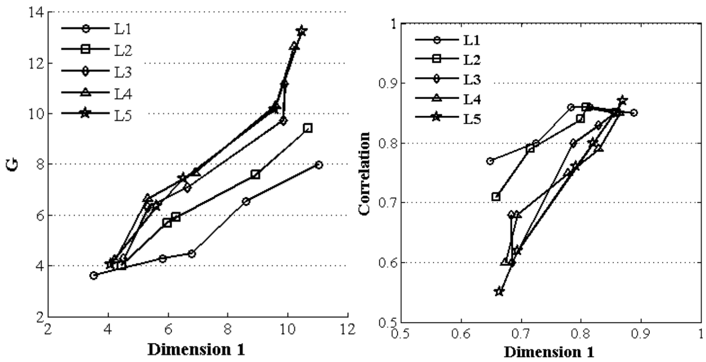


Figure 14. Left, relationship between the first dimension and the graininess parameter calculated by the BYK-mac-i multi-angle spectrophotometer. Right, relationship between the first dimension and the correlation parameter calculated by the gonio-hyperspectral system.

After this first analysis, a new visual experiment was conducted by applying the same methodology explained above. From the visual data, a preliminary measurement scale for graininess was developed, in order to be proposed as CIE recommendation. The scale is linearly correlated with visual data and traceable to standards of optical radiation metrology (Figure 15).

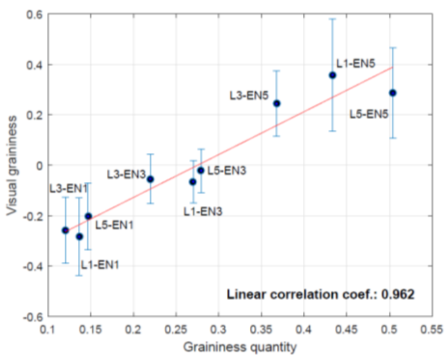


Figure 15. Relation between visual graininess and the graininess quantity calculated from METAS's reflectance measurements. The error bars represent the interobserver standard deviation. Note that the values of visual graininess only can be interpreted in relative terms, and they can be negative.

To summarise, the project successfully achieved the objective by a) providing and testing a new protocol for measurement of sparkle and graininess, b) developing psychophysical experiments to better understand the visual sensation of sparkle and graininess, c) creating of a CIE JTC at a global level to normalize a new approach for the quantification of sparkle.

5 Impact

A project website was created (www.birdproject.eu) and at the end of the project received more than 47,000 visits, it also had a restricted area for the 42 registered stakeholders. To promote the uptake of the outputs of this project by the wider stakeholder community, 9 newsletters were disseminated during the duration of the project. The partners have given 37 oral and poster presentations at national and international conferences, which included 6 invited talks. 10 peer reviewed open access papers have been published and one recently accepted.
A total of 6 formal progress meetings (including the kick-off) have been held with the participation of several stakeholders from more than 20 countries. Key events included:

- The consortium fostered a strong relationship with stakeholders and sought feedback into different parts of the project e.g. manufacturers of spectrophotometers were involved in the discussion of the main requirements of the universal BRDF data file.
- The consortium organised 3 workshops during the lifetime of the project.
    - In October 2018, a one-day workshop entitled "Open questions on gloss measurement" was organised, which covered all aspects of gloss, from cognitive science to virtual rendering. The CIE JTC17 (D1/D2/D8) (Gloss) was introduced to the 22 stakeholders who attended the workshop.
    - In May 2019, a workshop entitled "Open questions on visual appearance" was held, which was attended by 32 individuals (Master and PhD students, industrial stakeholders and academics).
    - In November 2019, a workshop entitled "the measurement of Sparkle and Graininess" was held and attended by 44 individuals, including 26 stakeholders. Several industrial stakeholders gave talks.
- In June 2020, the consortium organised two tutorials during the CIE events on colorimetry and visual appearance. One on "Advanced BRDF measurements", that was chaired by the project coordinator), and one on "Sparkle and Graininess", that was chaired by BiRD's Work Package leader on Sparkle and Graininess. Outputs of the project were presented at both tutorials were attended by 65 individuals.

The project was in effective contact with its industrial stakeholders (e.g. manufacturers of spectrophotometers), who participated at progress meetings, workshops, CIE TCs and tutorials as attendees or speakers. Round tables and breakout sessions have been organised during each event to facilitate discussion and exchanges.

Impact on industrial and other user communities

The recommendations on BRDF, sampling strategy, sparkle, gloss and file format have been made available to stakeholders and end-users from different industrial sectors e.g. instrument manufacturers, automotive, cosmetics, pulp and paper and printing industries. From a general point of view, the quality control of paints in automotive, cosmetic, packaging or other sectors will benefit from these recommendations, since they allow noticeable colour, sparkle or gloss differences to be avoided through good practice or better optimised instruments

The uptake of the outputs of this project by the industrial community will enable the future development of novel instruments which will increase the competitiveness of European industries. The recommendations on the optical parameters for the measurement of BRDF will be crucial for instrument manufacturers to produce a new generation of spectrophotometers and to enable industries to move from visual evaluation to objective BRDF measurement, leading to better control of the appearance of their products and less rejection by the customer. The uptake of adequate and trusted definitions of measurands and measurement procedures for sparkle and graininess that have been proposed in this project will enable the design and development of dedicated instruments, which will benefit in particular the automotive industry, where more than 90 % of car paint show sparkle effect and where the need of a reliable and traceable measurement is urgent. The uptake of the recommendations for the characterisation of the full BRDF of goniochromatic visual effect pigments will support the production of multi-angle spectrophotometers and promote the confidence of end-users that the best geometries can be used to characterise the product.

Impact on the metrology and scientific communities

In the absence of standardisation, the primary facilities developed at NMIs (PTB, CNAM, CSIC, METAS, CMI, CI, KU Leuven) for measuring BRDF have been made to be very versatile in order to satisfy particular customer requirements. In some cases, this increases the measurement time and the measurement uncertainty. The take up of the technical recommendation on BRDF, which will be made available to the metrology community by CIE TC2-85, will enable NMIs to develop transfer reference facilities based on commercial instruments developed by stakeholders of the project. With the new technical recommendations, existing calibration services can be automated at the NMI and calibration laboratory level, resulting in a reduction of calibration costs and time, and improvement of the traceability.

The normative work carried on in this project supports the development of a new generation of spectrophotometers that will increase the need of calibration and traceability. As a result, the metrological community will have to develop new calibration services to support for example automotive, cosmetics, pigments, packaging and 3D printing industries).

Sparkling is a challenging effect that presents a huge radiance dynamic in a very narrow angular angle. For the measurement of sparkle and graininess, NMIs have integrated Imaging Radiance Measuring Devices (IRMD) in their goniospectrophotometers. Work carried out on sparkle improve the metrology for the characterisation of IRMDs, which has an impact in near-field radiometry and hyperspectral techniques, and triggers the development of NMI capabilities in this field. The outputs of this project are already being taken up by other ongoing projects (e.g. EMPIR JRP 18SIB03 BxDiff and EMPIR JRP 16NRM02 SURFACE).

Impact on relevant standards

This project had a direct impact on different standardisation bodies working on new or improved standards, in particular:

- CIE TC2-85, whose aim is to provide geometrical recommendations for the BRDF measurement according to the type of sample under investigation.
- CIE JTC12, whose aim is to provide a methodology to measure sparkle and graininess, and to develop a measurement scale.
- CIE JTC17, whose aim is to provide recommendations for standardised visual assessment conditions of gloss and to make recommendations for the definition of a standard gloss observer.
- CIE TC 2-92, whose aim is to provide an internationally agreed-upon data exchange format supporting most lighting applications

The outputs of this project have been disseminated to these committees through technical reports and oral presentations at each JTC and TC meeting. The BRDF datafile format has been introduced to users of CIE TC4-50, *Road Surface Characterization for Lighting Applications*. National e.g. DIN NA 002-00-07 AA, SIS/TK 157, and international e.g. ISO/TC6, ISO/TC174/WG03 standardisation bodies were also briefed on the project's results at committee meetings. Members of the CIE TC2-85, DIN- FNF/FNL, "Farbmetrik" and of DfwG WG "Multigeometrie", were updated about the progress of this project by oral presentations given during their annual meetings.

Longer-term economic, social and environmental impacts

So far, no standard observer exists for gloss but it is now possible to define a CIE gloss standard observer. This will enable the development of new gloss measurement devices and management of gloss, based on measurements and not on visual assessment. Gloss measurement can then be integrated into CIE colour appearance models to help manufacturers predict or control the appearance of their product. In the long term, this is expected to have an economic impact for industries where the control of gloss is crucial, i.e cosmetics, 3D printing, textile, pulp & paper.

Following on from the pre-normative work undertaken by this project on BRDF, it will be possible for CIE, in the future, to adopt a standard observer based on the full BRDF measurement, potentially facilitating the management of the appearance as a whole.

6 List of publications

1. G. Ged, “Métrologie du brillant, développement et caractérisation psychophysique d'échelles de brillants”, PhD Thesis, September 2017 (link)
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3. T. Quast, A. Schirmacher, K.-O. Hauer, A. Koo, “Polarization properties and microfacet-based modelling of white, grey and coloured matte diffuse reflection standards”, Journal of Physics, vol **972** (2018). DOI 10.1088/1742-6596/972/1/012024 (link)
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5. F. B. Leloup, J. Audenaert, P. Hanselaer, “Development of an image-based gloss measurement instrument”, J. Coat. Technol. Res, **16** (4), pp 913-921, (2019). DOI 10.1007/s11998-019-00184-8 (link)
6. A. Ferrero, N. Basic, J. Campos, M. Pastuschek, E. Perales, G. Porrovecchio, M. Smid, A. Schirmacher, J.L.Velázquez, F.M. Martínez-Verdú, “An insight into the present capabilities of national metrology institutes for measuring sparkle”, Metrologia **57** 065029 (2020). DOI 10.1088/1681-7575/abb0a3 (link)
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9. G. Ged, A. M. Rabal, M. Himbert, G. Obein, “Assessing gloss under diffuse and specular lighting”, Color Research & Application 45, 591-602 (2020). DOI 10.1002/col.22510 (link)
10. A. Ferrero, “Theoretical evaluation of the impact of finite intervals in the measurement of the bidirectional reflectance distribution function”, Journal of Coatings Technology and Research 1-10 (2019). DOI 10.1007/s11998-019-00241-2 (link)

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

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