# Publishable Summary for 16NRM08 BiRD
# Bidirectional Reflectance Definitions

## 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.

## 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.

## 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.

**Progress beyond the state of the art**

According to the type of sample, BRDF measurement results can greatly depend on the measurement settings. This project has categorised visual effects in different categories (quasi lambertian, neutral, isotropic chromatic, glossy, goniochromatic based on interference pigments and goniochromatic based on diffractive pigments). For each category, the influence of the solid angles, the spectral bandwidth, the polarisation, the shape and the size of the illuminated area have been tested and a threshold of 5 % error has been computed for each parameter and each type of visual effect. Additionally, novel knowledge on BRDF regarding effect of coherence or of polarisation of light have been created. This work has been disseminated to CIE TC2-85 as a necessary step to standardise BRDF measurements.

As a result of the measurements performed in this project, the consortium was able to recommend sampling strategies of the BRDF space for each category of samples with an estimate of the error made in the reconstruction of the full BRDF. For goniochromatic samples, 10 geometries are enough if the user accepts an average error of $\Delta E = 5$. Around 70 geometries are necessary to drop at $\Delta E = 3$. For gloss samples, the sampling strategy is expressed as an angular step requested to measure the specular peak. This step can vary from 1.5° to 0.03° according to the level of gloss.

A convenient method has been proposed to arrange BRDF data to facilitate communication between NMIs, instrument manufacturers and industry using BRDF data. The file structure is based on JavaScript Object Notation (JSON) to keep the readability of the file and allow the possibility of returning metadata without the need of additional parsing. A visualisation software has been developed to provide open access visualisation of the variation of the BRDF with the direction of observation, for i) one specific direction of illumination, ii) one wavelength and iii) one polarisation. In the case of goniochromatic samples, colour differences and tolerances for 2D and 3D objects are implemented in this applet.

A new CIE Technical Committee, JTC17, has been set up with the objective to propose standardised assessment methods and improved optical evaluation methods for the quantification of gloss. The consortium brought to this technical committee expertise in BRDF measurement of the specular peak, psychophysical scales and a new type of BRDF measurement coming from a new setup developed in the project. All this material will support the objective of this technical committee to define a "standard" observer, which is based on the average result from a number of observers, taking into account one or more predefined sets of assessment conditions.

As a result of a proposal formulated by the project partners, a new CIE Technical Committee, JTC12, has been established to work on the standardisation of sparkle and graininess of coatings. A measurement protocol to quantify the sparkle effect has been proposed and tested to provide high inter laboratory comparability. A measurement protocol has been also set up to quantify graininess. Both measurements based on both protocols correlate well with visual scales of sparkle and graininess that have also been assessed and set in the frame of the project. All these results have been provided to JTC12 in order to support its work on a future normalisation of the measurement of sparkle and graininess.

**Results**

*Standard parameters for measuring BRDF*

A categorisation of samples and a definition of angles of illumination and detection was accepted by CIE. It was agreed that:

- all angles must be defined according to the normal of the sample;
- the recommendation for BRDF measurements would concern quasi-lambertian, neutral (achromatic), non-neutral (chromatic), gloss and goniochromatic (including "interference pigments" and "diffractive pigments") samples;

- sparkle, graininess, spatially non-isotropy, brushed metals fabrics and textile would not be covered by the recommendation.

The impact of using finite intervals for the measurement area, irradiation and collection apertures, and solid angles has been examined for the measurement of BRDF. A theoretical approach has been proposed to evaluate the limitations of experimental systems and to account for the relative error due to finite intervals. This error, calculated as the relative difference between a biconical integration of the BRDF and the actual BRDF, is decomposed in two main factors, which are related to the scattering distribution function of the surface, and to the geometries of the incident and collected radiant fluxes. A general rule for experimentalists has been provided to help for 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 (see here).

When evaluating the gloss of a surface, observers look in and around the specular direction and explore the specular peak of the surface's BRDF. In order to progress in the comprehension and measurement of gloss, it is necessary to access the height, width and even the shape of the specular peak. But this peak can be narrow and important measurement errors can be done if the optical settings of the measurement system are not adapted. Using a dedicated goniospectrophotometer, the specular peak of the NCS® gloss scale with samples varying from matt to full glossy has been measured. From these traceable and metrological measurements, the settings required to access a reliable BRDF of the surface in the specular direction according to its gloss level measured with a classical glossmeter can be recommended. For gloss values higher than 60 GU, the angular resolution should be lower than 0.05° (see here) to avoid a deviation higher than 5 % from the correct value.

The impact of using non-infinitesimal spectral and angular bandwidths has been assessed 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. 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 (see here). In parallel, the sampling angular strategy to be adopted for the characterisation of goniochromatic effects, coming from interference (here) and diffractive pigments (here) has been elaborated and has been adopted by CIE TC2-85 in June 2019.

The study on the effect of the shape of the illuminated area has shown that this effect can be neglected on diffuse as well as on glossy samples. Size and homogeneity of the illuminated area, at the opposite, may have an effect, particularly when it is associated with a narrow spectral bandwidth and/or a high collimated beam. Results on this topic have been presented to CIE TC2-85 and further investigation has been engaged in EMPIR JRP 18SIB03 BxDiff.

Finally, to elucidate the influence of polarisation in reflectometry, measurements in several bidirectional geometries of different types of matte reflection standards have been performed and the Stokes parameters have been determined. The dependence of the polarisation on the sample type, wavelength and geometry have been studied systematically and the main influence factors have been identified: The effect is largest at large angles of incidence or detection and at wavelengths where the magnitude of the reflectance is small. In addition, the results for the colour standards have been modelled using a microfacet-based reflection theory. Although the theory is very simple and only has three free parameters, the agreement with the measured data is very good and all essential features of the data can be reproduced by the model (see here).

This objective was achieved.

*BRDF data handling and processing*

A review on existing commercial colour management software for colour quality control of surface appearance has been done. A set of BRDF file formats used in commercial devices (multi-angle spectrophotometers, gonio-spectrophotometers, etc.) and theoretical models has been collected by the project partners from industrial stakeholders, rendering software designers, and international standards (American Society for Testing and Materials (ASTM), CIE, etc.). From this survey, and after discussion in progress meetings, a datafile format was agreed by the consortium 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 consortium tested the proposal for one year and proposed ameliorations. The final version was adopted by CIE and can be consulted here.

Classical appearance descriptors used in academy or industry e.g. polar mode, colour travel, digital RGB visualisation, etc. have been collected and reviewed. Outputs have been presented and discussed with the project's stakeholders at a progress meeting. From this discussion, an open-source code named BiRDview has been designed using Python, whose main function is to show BRDF measurements from different equipment. In addition, different appearance descriptors as colour travel or digital RGB visualisation have been considered to obtain a complete material characterisation. The applet can be used by any stakeholder or general public. It takes as input file measurement data formatted in JSON. It is available on BiRD's website, section "Project results" (here).

This objective was achieved.

*Gloss measurement and visual perception*

The state-of-the-art of gloss measurement and gloss perception has been summarised in a Technical Report that was sent to CIE Division 1. Together with the report, a database of key research related to the subject was developed and made accessible on the project website (here). Specific terminology related to gloss, encountered in ISO standards, was summarised in a glossary of terms, together with their definition and reference to the defining standard(s). KU Leuven submitted a proposal on the creation of a Technical Committee on gloss to CIE Division 1. The Board of administration of CIE proposed to make it a joint TC, including CIE divisions 1 (vision and colour), 2 (Measurement of light) and 8 (Image technology). The proposal was accepted and "JTC17 (D1/D2/D8): Gloss measurement and gloss perception: A framework for the definition and standardisation of visual cues to gloss" is now active with 12 members.

A new measuring equipment devoted to the measurement of gloss was developed at KU Leuven. This device, with an optical design based on ISO 2813 recommendation, proposes advanced features that allow accessing the shape of the specular peak and materials visual properties like "orange peel" or "contrast gloss" (More details are here).

A psychophysical experiment with the objective to quantify the effect of the type of illumination and of the surrounding on gloss perception was conducted. Evaluations have been done in a dedicated light booth that allows simulating "cloudy sky" or "sunny sky" light, with poor or hight structured surround. This experiment allowed to conclude that for most of the situations, the concept of gloss constancy is valid, and the type of lighting and surround have a negligible effect on gloss perception regarding the influence of surface parameters. Nevertheless, results show that gloss constancy is broken in the region of matte samples. It could be demonstrated that the visual system is very sensitive in the mattes, and that particular care has to be taken with the lighting conditions for this category of samples (see here).

This objective was achieved.

*Sparkle measurement and visual perception*

A proposal for the creation of a CIE TC was prepared by CSIC and accepted by CIE. A Joint Technical Committee (JTC12) was established that involves CIE divisions 1, 2 and 8. This JTC has 21 members. A first draft on sparkle and graininess measurement has been submitted to the JTC for review. It includes methodology for the spectrophotometric measurements, definitions and concepts regarding contrast threshold, and a physical model which can describe both sparkle and graininess. It was concluded that new and independent testing experiments are required.

The definition of sparkle and a methodology for its measurement were developed, based on works done in a previous EMRP project (see xDReflect) and on a clear methodology for the acquisition of sparkle images. To test it, a set of nine samples representing the full range of sparkle were selected and circulated among CSIC, PTB, METAS and CMI. Each of these NMIs have developed a setup to perform measurements according to the methodology proposed. Some issues regarding the methodology were observed, and a second measurement campaign was carried out with an improved method. In parallel, a full psychophysical study was set up and performed to validate the linearity between the visual sensation of sparkle and the instrumental measurement scale proposed. In the end, was shown that the measures correlate excellently with the sparkle visual data. The results support the sparkle measurands defined as adequate quantities for defining the standard measurement scale of sparkle claimed by industry (see here).

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.

An equation to relate the reflectance-based quantities and, indirectly, the structural variables with the visual data of graininess has been proposed (see here) and shared with JTC12. An evaluation of the graininess as visual attribute was made by means of a psychophysical experiment and a multidimensional scaling algorithm. The results revealed that two dimensions are needed to characterise the graininess effect. A good relationship with the optical measurement proposed by the consortium was observed with the dimension 1. However, no relationship was established with dimension 2 (see here). Based on these conclusions, further research is necessary that focuses on the new imaging processes and a new visual experiment.

This objective was achieved.

**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.

**List of publications**


1. G. Ged, "Métrologie du brillant, développement et caractérisation psychophysique d'échelles de brillants", PhD Thesis, September 2017 (link)

2. A. Ferrero, J.L. Vázquez, E. Perales, J. Campos, F.M. Martínez-Verdú, "Definition of a measurement scale of graininess from reflectance and visual measurements", Opt. Express **26**, 30116-30127 (2018). DOI 10.1364/OE.26.030116 (link)

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)

4. E. Perales, F.J. Burgos, M. Vilaseca, V. Viqueira, F.M. Martínez-Verdú, J. Pujol, "Graininess characterization by multidimensional scaling", Journal of modern optics, **66** (9), pp 929-938, (2019). DOI 10.1080/09500340.2019.1589006 (link)

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)

7. A. Ferrero, J. Campos, "Angular and Spectral Bandwidth Considerations in BRDF Measurements of Interference-and Diffraction-Based Coatings", Coatings 10, 1128, (2020). DOI 10.3390/coatings10111128 (link)

8. E. Perales, B. Micó-Vicent, K. Huraibat, V. Viqueira, "Evaluating the Graininess Attribute by Visual Scaling for Coatings with Special-Effect Pigments", Coatings 10 1-10, (2020). DOI 10.3390/coatings10040316 (link)

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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| Project start date and duration: | | 1 May 2017, 40 months |
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| Chief Stakeholder Organisation: CIE | | Chief Stakeholder Contact: Kathryn Nield |
| Internal Funded Partners:<br>1 CNAM, Paris<br>2 Aalto, Finland<br>3 CMI, Czech Republic<br>4 CSIC, Spain<br>5 PTB, Germany<br>6 RISE, Sweden | External Funded Partners:<br>7 Innventia, Sweden<br>8 KU Leuven, Belgium<br>9 UA, Spain | Unfunded Partners:<br>10 CI, New Zealand<br>11 METAS, Switzerland |
| RMG: - | | |