Publishable Summary for 18SIB03 BxDiff
New quantities for the measurement of appearance

Overview

Product appearance and visual branding are important drivers for consumer purchase decisions, as they underpin perceptions of 'quality' and 'desirability'. The project aimed to advance primary metrology in spectrophotometry to meet industrial needs for the quantitative measurement of appearance. This was accomplished by i) defining new spectrophotometric quantities, ii) taking previously ignored corrections terms into account, and iii) developing new traceable spectrophotometric primary references to provide new tools for quality control and more realistic solutions for virtual prototyping. This research aimed to benefit different industrial sectors like automotive, paper, cosmetic, 3D-printing and virtual reality rendering as well as scientific related applications like aerospace missions.

Need

Industry is developing increasingly complex materials that produce visual effects made to look beautiful and appealing (like iridescence or sparkle), or to accomplish a given function (like retroreflection). To develop and control their appearance properties, traditional colorimetry is not adapted anymore, and industrials increasingly start to use bidirectional reflectance measurements in various contexts. Traditional reflectance references based on a single angular measurement configuration will be deemed obsolete in the future. New commercial bidirectional spectrophotometers are diverse, flexible and high performing. National Metrology Institutes (NMIs) must continue supporting the ongoing revolution in spectrophotometry by providing bidirectional reflectance calibration services for angular configurations in addition to the classical 0°:45° configuration. The primary scales kept by participating NMIs have never been compared for e.g. out-of plane angular configurations that are representative of those used in the new generation of commercial products. Furthermore, the influence of common optical phenomena like speckle and polarisation has never been thoroughly studied in Bidirectional Reflectance Distribution Function (BRDF) measurements and might have a non-neglecting effect in uncertainty budgets.

The appearance of objects depends not only on the material(s), colour, shape and lighting environment, but also on the observation distance and object size. Therefore, the optical properties of materials must be measured at different scales: from the macroscopic to the microscopic.

Bidirectional Transmittance Distribution Function (BTDF) as a quantity, is the angle dependent radiance in transmission, referred to the irradiance on the sample. While BTDF measurements have been widely carried out, a standard definition for this measurand does not currently exist. BTDF measurements are of interest for diverse applications ranging from diffusers for aero-space applications, for green-houses, luminaires and to functional glasses for photovoltaic panels, because they could allow better performance, characterisation and efficiency. Thus, the measurand of BTDF must be studied, primary facilities must be set up and traceability must be consolidated with sphere-based measurements.

Total appearance, as defined by the International Commission on Illumination (CIE), is the contribution of four main visual attributes: colour, gloss, texture and translucency. Currently, there is no metrology infrastructure in place for measuring translucency, even though this attribute is ubiquitous and crucial in many fields such as cosmetics, food, packaging, dermatology, architecture, virtual reality and 3D printing. Quantifying translucency requires traceable measurements of the Bidirectional Scattering Surface Reflectance Distribution Function (BSSRDF), which are not presently available.

Objectives

The overall goal of this project was to advance primary metrology in spectrophotometry. This involved defining the new quantities Bidirectional Transmittance Distribution Function (BTDF) and Bidirectional Surface Scattering Reflectance Distribution Function (BSSRDF), developing primary facilities for their realisation, and further improving the measurements of Bidirectional Reflectance Distribution Function (BRDF). The specific objectives of the project were:

1. To address advanced metrological issues, i.e. speckle and polarisation, related to measurement of the BRDF with the aim to reduce the measurement uncertainty by a factor of two, down to 0.1 % (k = 2) in the visible wavelength range,
2. To establish a full metrological traceability of the BRDF from very small objects (micrometre scale) to regular objects (centimetre scale),
3. To develop primary reference facilities and reference samples (artefacts) for the measurement and dissemination of the BTDF as a traceable quantity with a relative target uncertainty of 0.5 % (k = 2),
4. To develop primary reference facilities and reference samples (artefacts) for the measurement and dissemination of the BSSRDF as a traceable quantity with a relative target uncertainty of 5 % (k = 2),
5. To facilitate the uptake of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, spectrophotometer manufacturers), standardisation organisations (ISO, CIE) and end users (e.g. automotive industry, video game developers, healthcare sector, visual arts sector, architectural materials manufacturers).

Progress beyond the state of the art

Improvement of the measurement uncertainty of BRDF

Building on previous projects EMPR IND52 - xDReflect and EMPIR 16NRM08 - BiRD, the measurement uncertainty for BRDF measurements was improved by addressing advanced metrological issues such as polarisation and speckle induced side effects. The project aimed to go beyond the state of the art on this by reaching an uncertainty of 0.1 % (k=2) at 550 nm on white diffusing samples. Additionally, to address the growing need for calibration points performed out-of-the-plane of incidence, the first comparison of BRDF scales realised with primary facilities was performed at angular geometries including out-of-plane geometries.

Metrological traceability of the BRDF from micrometre to centimetre scale

Metrological traceability of BRDF was extended by focusing on specific metrological issues related to scalability of BRDF measurements of small size area. These issues must be understood and accounted for, along with the requirements for such measurements. For the first time, a clear and traceable link between micrometre scale measurement areas and centimetre scale measurement areas is provided.

Primary reference facilities and standard artefacts for BTDF

The most important classes of diffusers were reviewed, for the determination of the measurand for BTDF with the lowest uncertainty. Two dedicated primary BTDF facilities were developed to provide traceability for different sample classes or types, like frosted glass and volume diffusers. The congruence of the scales was verified by a comparison, aiming at an expanded uncertainty of 0.5 % (k=2). The traceability was tested in a second round of comparisons using existing gonio-spectrophotometers at NMIs, as well as commercial set-ups.

Moreover, a greater insight into the precise BTDF was investigated in order to improve the results obtained with existing integrating sphere measurements, as the results for artefacts with properties being far off from the Lambertian model may generate considerable errors.

Primary reference facilities and standard artefacts for BSSRDF

At present, the BSSRDF is not clearly defined as a physical quantity. Moreover, because no primary measuring equipment exists, traceable measurements of subsurface scattering or translucency cannot be provided. BxDiff went beyond the state of the art by defining the measurand and developing primary reference facilities and standard artefacts for the measurement and dissemination of the BSSRDF as a traceable quantity, with a targeted uncertainty of 5 %. Based on accurate BSSRDF measurements, scattering and absorption coefficients of materials as well as the phase function, was computed. This was the first step towards calibration and measurement capabilities for BSSRDF at NMIs.

Results

Improvement of the measurement uncertainty of BRDF

Existing goniospectrophotometers at participating NMIs and DIs (METAS, CI, CMI, CSIC, PTB, CNAM) have been upgraded to decrease their uncertainty before the interlaboratory reflectance scale comparison. After a detailed study on effects of rotations errors on goniometric measurements published in Metrologia (link), CI has entirely rethought the way they control the rotation of the sample by replacing their robot arm by independent rotation stages, which gives a better angular control. CNAM and CMI have modified the optical design of the illumination part of their setup to include a control of polarisation. CSIC has added a second polariser to its existing facility in order to finely study the effect of polarisation on BRDF measurement. As this work focused on BRDF & polarization, a paper that describes methodology to assess polarization-related effects for the measurement of the BRDF has been published in Metrologia in June 2020 (link). Relative systematic errors due to polarizing conditions are calculated as a combination of the instrument polarization bias and sample type, for four different samples, classically used for BRDF calibration. The impact of the proposed methodology on the uncertainty is discussed. This methodology has been applied by the participants implicated in the comparison of BRDF scales in order to help to decrease the uncertainty of the comparison.

CNAM has modified its high angular resolution BRDF measurement facility to allow a control of the spectral bandwidth. It has allowed to show evidence of speckle effects in BRDF measurements. The impact of speckle on BRDF is more important when measuring glossy surfaces and becomes the major component of uncertainty for an angular resolution below 0.1° even with wavelength spectral bandwidth higher than 50 nm (V(l) spectrum for instance). To support this work, NCS modified their existing technique for producing NCS gloss scale to manufacture a large set of glass-based samples to be used for evaluating speckle effects in BRDF measurements. To achieve satisfactory results, this required a trial-and-error process when selecting and applying primers and paint to the glass. The result is a set of high-quality uniform samples with different levels of gloss well suited for the speckle task. In parallel, RISE has measured the microtopography of this gloss scale with different sampling steps and UJM has adapted the theory of speckle to the specific field of BRDF measurement. Thanks to these works; simulations of the BRDF based on wave optics and light-material interaction could be performed show results that are similar to measurements (see here). In parallel, CSIC adapted its goniospectrophotometer to reproduce the observation of speckle in BRDF measurements. When using the imaging mode, the speckle noise was observed while using a broadband illumination. The impact of this work is high, because we it can lead to a commercial glossmeter that proposes a measurement of the specular peak of surfaces with a resolution below 0.1°. Still on speckle, theoretical and experimental approach have been merged to find a way to clean the speckle from BRDF measurements. This work shows that NMIs are reaching a floor at the moment and a balance have to be found between measurement surface size, spectral bandwidth and angular resolution to keep the BRDF measurement valid. As a matter of fact, speckle is a phenomenon that comes from the coherent nature of light and BRDF is a radiometric quantity. Therefore, the consortium set out to investigate which quantity is measured when performing BRDF measurements with high angular resolution or narrow spectral bandwidth. A paper entitled “Advocating a statistical definition for the BRDF” where this question is discussed has been published in the journal of physics (here).

The first “in & out of plane” BRDF comparison has been carried out in 5 angular configurations: i) [45°:0°], ii) [0°:45°], iii) [45°:-60°], iv) [45°: (45°,90°)] and v) [45°: (50,1°, 33,4°)]. Measurements have been done at 550 nm on 3 samples (white diffuse, grey diffuse and white satin). Labsphere, the manufacturer of the well-known Spectralon material, supplied several samples sets for the comparison. These samples have been custom made to fit the consortium’s need for mounting and handling. METAS piloted the comparison with CI, CMI, CNAM, CSIC and PTB as participants. The reference value was computed using the Mandel-Paule method, where an interlaboratory uncertainty component is added to all participants' uncertainties until the data passes the Chi-square test. The process was executed for every sample and every geometry separately. A non-negligible interlaboratory uncertainty was needed to achieve consistency demonstrating some discrepancies between the participants BRDF scales. The most probable cause for the discrepancies is the underestimation of alignment uncertainty contributions (link).

About modelling BRDF, DFM extended the generalized Harvey Shack model to cover all outgoing angles for a given incoming angle and used BRDF data supplied by METAS to fit the parameters. A rendering tool based on NVIDIA OptiX has been developed by DTU and is ready for use. The tool has been updated, so that it enables to simulate a BRDF/BTDF measurement given topography data that describes the surface microstructure. With this approach, large surfaces could be rendered based on real BRDF measurements. Having these results, the project successfully achieved the objective.

Metrological traceability of the BRDF from micrometre to centimetre scale

To support the multiscale traceability study, a full collection of specific samples has been created. Two types of micropillar structured glass samples and five different types of glass fibre samples have been supplied by SG. Their general knowledge about glass and its potential for use as artefacts with specific properties being very helpful for the project. Samples showing regular cylindrical structures mimicking hairs and imitation leather have also been developed. Roughness standard on silicon substrate has been procured. Four series of textured samples made of white dots placed at scales spanning from 100µm to 1mm have been made and are available to support future developments in this field by the community. A bibliographic study on BRDF measurements of small size areas has been completed and is available on the project's website (here). Goniospectrophotometers have been developed at CNAM, CSIC, DFM and METAS to measure on small surfaces.

CNAM developed a µBRDF goniospectrophotometer. The illumination light beam is built with a Laser-Driven Light Source (LDLS) broadband light source associated with a specific optical system that allows illumination of the sample with a 50 µm diameter light beam. The detection is composed of a commercial spectrophotometer combined with a custom-made optic. It allows accessing the radiance inside a 300 µm area (link).

DFM developed a µBRDF set-up using a diode laser combined with a focusing lens to control the size of the measurement spot, which can reach mm scale diameters. The detection is a Si photodiod mounted on a rotary arm that scans the reflection angles in the horizontal plane The measurement is performed in an underfilled configuration, meaning that the measurement area is limited by the illumination area, which is smaller than the acquisition are of the detector.

The µBRDF setup at METAS performs relative measurements using a reference sample with traceability to PTB. The illumination is quasi-monochromatic using a commercially available tuneable light. A Köhler optical system ensures that the sample is illuminated uniformly with a quasi-collimated beam. The beam size of the illumination is adjustable, ranging from 200 µm up to 20 mm in diameter. The detector is a CCD camera. METAS can perform measurements either by changing the beam size and averaging over a larger measurement area, or by keeping the beam size large and selecting only a smaller measurement area.

CSIC modified its goniospectrophotometer, GEFE, by including a high sensitivity CMOS digital camera as a new detection system and a laser driven light source which, together with an optimization of the optical irradiation system, provide a uniform irradiance with size from 25 µm to 2 mm in diameter.

A comparison of the different µBRDF facilities has been performed at 0°/45° geometry, on white resina with surfaces that were small disks of 1000 µm, 500 µm, 300 µm and 100 µm. The conclusion of these works is that today, we are not capable to extend the BRDF scales maintained at our NMIs to such small size. The main issue is that we couldn’t find samples that keep their BRDF value constant at the different scales. As a matter of fact, we discovered that at such a small scale, all classical materials used as BRDF standard artefacts are translucent and thus have a BRDF that depends on the size of the measured surface. Therefore, it was not possible for each NMI to test the stability of their µBRDF facility when decreasing the measurement area, because we couldn’t know if the difference came from the sample or from the facility. It was also not possible to do fine comparison of the different facilities because each had a different beamsize. Nevertheless, the consortium learnt a lot on this topic during the duration of BxDiff and will come back later with new ideas to validate the BRDF scale on small measurement size. A full report has been edited on these works and is available on demand. Having these results, the project successfully achieved the objective.

Primary reference facilities and standard artefacts for BTDF

A “measurand team” agreed on a specific set of samples and geometries suitable for the proposed BTDF comparisons and on the definition of the measurands. A possible link between BSSRDF and BTDF measurands, discussed in the “measurand team” was worked out in more detail and lead to the publication of a scientific paper (here).

Twelve complete sets of samples for different BTDF intercomparisons and refractive index determination were prepared by PTB, RISE, and Covestro. Each set contains five different samples with varying scattering properties in order to cover most types of commonly used diffusers. In cooperation with Temicon, specialized holographic diffusers have been made available to push measurements facilities to their limits. Innventia has developed four types of cellulose nanofibrillar (CNF) films with different scattering properties.

To determine BTDF of diffusely transmitting materials, two new primary facilities have been independently developed at PTB and Aalto. The performance of both facilities has been compared by a bilateral comparison on two different diffuser types, one with a Lambertian, the other with a Gaussian scattering characteristic. The BTDF was determined in both in-plane and out-of-plane bidirectional geometries at four different wavelengths in the visible spectral range. A thorough analysis of the measurement uncertainty shows a combined k = 1 standard uncertainty of 0.8 % - 1.2 % (PTB) and 1.3 % - 1.7 % (Aalto). The BTDF results obtained agree well within their expanded k = 2 uncertainty, indicating that both facilities are suited as primary reference setups for the determination of the BTDF.

To test the traceability of the BTDF scale, two parallel multilateral scale comparisons on BTDF were performed between National Metrology Institutes (NMIs), Designated Institutes (DIs) and industrial partners, to get an insight on existing European measurement capabilities and gain experience in the characterisation of a larger variety of different diffusers. In the first group of comparison, 6 NMIs (PTB, DFM, CMI, CI, CNAM and Aalto) have dealt with samples of three different scattering characteristics in different in-plane geometries, focusing more on orientation-dependent (azimuthal) scattering properties. In the second group of comparison, three home-built and three commercially available measurement setups were involved, with the emphasis lying on the scattering magnitude and sample thickness.

The measurement results were analysed. Because of the enormous amount of data, the completion of a ready for submission paper will take substantial efforts that will bring us later in 2023. However, it can be foreseen that the quality of the results will give an excellent overview of the European capabilities in performing high-class BTDF calibrations and will also show specific sample-related problems to be solved for improved future BTDF measurements. Based on this knowledge collected during these measurements, a "Good practice guide for the measurement of BTDF" has been written and put available on BxDiff website (link)

In parallel, MSL, CNAM and Innventia investigated the use of goniospectrophotometry to understand and improve the current sphere-based methods of measuring transmittance haze. Three samples were selected for this study: A cellulose nanofibrils sample fabricated by Innventia, a commercial holographic diffusing sample, and a nominally 0.5 mm thick piece of sintered halon made at CI. CI calculated the transmittance haze values from CNAM and CI goniospectrophotometric BTDF measurements and compared them to measurements using the ISO 14782 method on their integrating sphere. They found that the two results did not agree. Upon consideration, this is not surprising. Because of the large beam size in the sphere measurements, the diffuse transmittance component meant to capture all light scattered by more than 2.5° actually includes some light scattered by only 1.3°, while some light scattered to as much as 6.7° is not included. The difference between the integrating sphere haze and the true haze (i.e., conforming to the definition and obtainable from the BTDF measurements) therefore depends on the shape of the BTDF in this range of angles.

About modelling BTDF, KUL has received from Covestro different translucent samples with three different thicknesses for each and BTDF measurement data from other partners. The samples have no surface roughness - only volume scattering. KUL tried fitting to these measurements with the Henyey-Greenstein (1-parameter) and Gegenbauer-Kernel (2 parameters) models. Only fitting with the Gegenbauer-Kernel phase function model was found to give good correspondence with the measurements. The parameters obtained with the Gegenbauer-Kernel phase function model were then used to predict the BTDF of thicker samples. The simulation was compared with the measurements, leading to very good. Also predictions of the transmitted 0° observer luminance proved to be quite accurate for the different sample thicknesses. But despite these good fittings and predictions, there remains a certain error in the obtained parameter values. This error becomes apparent when analyzing the wavelength dependency of these values. This remaining error can be attributed to the so-called similarity problem: i.e. multiple parameter-sets produce the same optical performance attribute, making it impossible to derive the "correct" parameter set from measurements of this optical performance attribute (i.e. the BTDF of the sample - in this case). In order to resolve this similarity problem, one can consider more complete optical performance attributes (e.g. the BSSRDF of the sample). KUL therefore tested if the BSSRDF of the Covestro sample could be predicted with the extracted volume scattering material properties. But this was not to the case. Two possible causes of this discrepancy will have to be investigated in future: (1) the impact of surface scattering on the BSSRDF or (2) a fundamental discrepancy between the experimental BSSRDF measurement configuration at KUL and the simulated illumination/detection configuration. Having these results, the project successfully achieved the objective.

Primary reference facilities and standard artefacts for BSSRDF

CSIC, in collaboration with CNAM, DFM, DTU and UJM, has reviewed existing theoretical and experimental work on BSSRDF. A reportership has been opened by CIE Div2 on “Definitions for bidirectional scattering surface reflectance distribution function (BSSRDF)” with the label DR2-86.

Discussion on the definition on BSSRDF measurement has quickly merged with the one of the BTDF measurand. The “measurand team” had a thorough discussion and both measurands have been defined. Names, symbols and measurement equations have been agreed and this forum published an important article in Optics Express (link). This paper discusses the adequate use of BRDF, BTDF and BSSRDF quantities when assessing translucent materials. For these materials, the radiance in a given direction depends not only on the directional irradiance but also on the size of the irradiated area of the surface, because for translucent materials, the radiance is produced by both the in-surface reflection and the sub-surface scattering. By explicitly considering both contributions, two other scattering quantities have been defined: one that accounts exclusively for the in-surface reflection and the other that accounts for sub-surface scattering. In this regard, these quantities might be considered more fundamental than BRDF, BTDF and BSSRDF.

Stakeholder Covestro, the manufacturer of different type of polymers, has been collaborating closely with the project partners to produce several sets of custom-made samples for BSSRDF measurements. By adding particles of different size, material and concentrations to polycarbonate in a well-controlled process, samples with suitable scattering properties were achieved.

CSIC has developed an image based BSSRDF primary facility for measuring the BSSRDF with an expanded uncertainty lower than 5 %. This facility uses camera detection and a spectral narrowband light source irradiation. It is based on the measurement of the spatial distribution of the reflected luminous flux when irradiated with a sub-centimetre spot size. A peer-review article, describing design, principles, measuring procedure, measurement equation and uncertainty budget has been published in Optics Express (link). CNAM has modified its µBRDF goniospectrophotometer (see above in section on multiscale traceability) to perform BSSRDF measurement by mounting the detection on a 2-axis translation stage. CNAM used this setup to measure the BSSRDF of sintered PTFE, a material that presents a very low translucency, visible only at small scales. The measurement results have been validated using numerical simulations and BRDF measurements done with CNAM’s reference goniospectrophotometer. However, the measurement capabilities of this setup are limited to samples of very low translucency like sintered PTFE. When the sample is of medium to high translucency, the signal-to-noise ratio is not sufficient anymore. Therefore, for the measurement comparison of BSSRDF scales performed with Covestro samples, CNAM replaced the CS2000 by a luminancemeter with a greater sensitivity, but a larger area of measurement. An article describing the set has been submitted to Applied Optics and is under review.

KUL developed a third facility to perform BSSRDF measurement. It is a near field goniophotometer using a Imaging Luminance Measurement Device where the light source has been modified. It consists of a green laser diode collimated to have a beam width of 2.6 mm diameter on the sample. To perform BSSRDF measurements, the flux of the illumination beam is accessed with a BaSO4 sample with a known BRDF at 0°/45°.

Three Covestro samples have been measured by CSIC and CNAM to compare the primary BSSRDF scales and by KUL to test the quality of the traceability. The relative values of the BSSRDF measurements at KUL agree well with the previously obtained values from the comparison between CSIC and CNAM, and a calibration factor for this facility was obtained. We observed some dependence of this calibration factor on the geometry and on the position on the sample, which might be a consequence of the different realization of the bidirectional geometry and the size of the irradiated area.

From all these works, recommendations can be given for the appropriate selection of the detection system for different purposes of the BSSRDF measurement. A camera-based system should be more adequate for industrial applications, as it can provide BSSRDF measurements faster than using a detector without spatial resolution. In addition, we have shown that, although a conventional system based on a calibrated luminance meter might be used for providing traceability at very specific conditions, a camera-based system can be used for metrological applications too.

In the world of bidirectional spectrophotometry, even if it is now possible to perform traceable measurements, the data points are in most of the cases not enough to be exploited by end-users. Therefore, to fulfil the need, it is mandatory to interpolate value between measurement points using models. A literature study has been done to determine the state-of-the art in the field of modelling of light diffraction and propagation, with a special emphasis on translucent materials. It covers the different model categories as Monte Carlo path tracing, aperiodic rigorous coupled-wave analysis (ARCWA), finite difference time domain (FDTD) solutions, microfacet models, Rayleigh-Rice and Harvey-Shack models and colloidal suspension methods. This survey has been published in Computer Graphics Forum (link). Based on this work, the consortium has chaired and presented a full session with five presentations (2 from DTU, 2 from DFM, 1 from KULeuven) on "Acquisition of Optical Properties" at Eurographics 2020, the 41st annual conference of the European Association for Computer Graphics.

Those models were used to predict the BSSRDF of Covestro samples. DTU tested a neural representation of the measured data using a multilayer perceptron (MLP) model to enable a direct representation of the measured data. The benefit of the neural representation is that it eases interpolation and extrapolation of the measurements. Model's parameters are adjusted on BSSRDF measurements realized by CSIC. Then digital twins of the samples are generated using Monte Carlo ray tracing. Using the digital twins of our samples, DTU improved the estimated optical properties by comparison of photographs with renderings. The validity of BSSRDF models for different regimes of optical properties have been tested. In the case of more transparent samples, existing diffusion-based analytic BSSRDF models do not work. The reason is that these models were derived based on an assumption of a highly scattering material. Full volume path tracing can more accurately simulate more transparent materials. Volume path tracing is, however, a computationally expensive procedure for which it can be hard to avoid stochastic noise in the rendered image. The samples and measurements produced in the BxDiff project thus not only provides tools for estimating optical properties of translucent materials but also for validation of new BSSRDF models.

As an alternative to estimation of optical properties, DTU tried also to feed the measured data to a neural network that takes positions of incidence and emergence of the light as input as well as directions of incidence and emergence. Such a network is a neural representation of a BSSRDF and can be used for rendering images of the material that it represents. A fully connected network with four layers and a width of 128 nodes was used. The neural representation provided smooth results with plausible spatial variation of the radiance in the case of extrapolation, but the validity of these extrapolated results is currently unknown. Having these results, the project successfully achieved the objective.

Impact

The project website, which is hosted by CMI, has had almost 20,000 visits over the period of the project. Five progress meetings have been organized during the project that had on average 50 attendees including 60 % of industrial stakeholders from different sectors, e.g. pigments, spectrophotometer manufacturers, pulp & papers, automotive or cosmetics.

Fifteen publications have been published (or approved for publication) in peer reviewed journals. Four additional papers are still under review. Outputs of the project have been presented at 14 international conferences and 11 national conferences in France, Germany and Spain. Among these 24 presentations, 3 were invited talks. Members of standardisation groups (CIE, DIN, DfwG and ISO/TC6) have given 22 presentations during progress or annual meetings to inform members about BxDiff launch and results.

Due to the pandemic, workshop on BTDF measurement, on speckle and on Models had to be postponed to the end of the project but could be done (respectively on Apr 22, Dec 21 and Sept 22).

Impact on industrial and other user communities

The field of spectrophotometry is evolving quickly, and new commercial devices are continuously coming to the market. The appropriate characterisation and calibration of all these different types of goniospectrophotometers requires a coordinated effort between European NMIs. Thanks to BxDiff, the consortium is now able to provide BTDF calibration services to manufacturers of novel spectrophotometers, R&D industries and others. The effect of speckle is better known which has an impact on the calibration of glossmeters.

The reduction of the BRDF measurement uncertainty and the validation and improvement of BRDF scales reduces the uncertainty of the calibration for spectrophotometer manufacturers, which has an immediate effect at the industrial level.

The definition and realisation of BSSRDF scale has been done and will have a direct impact on different industries e.g. cosmetics, automotive, plastics, pulp and paper as well as on rendering software developers as it will provide the calibration solution for devices that have already been developed. Even if the uncertainty still needs to be decreased for this quantity, the first applications tested on existing models have allowed to better understand the limitations of the models, and the optical properties of translucent materials.

Impact on the metrology and scientific communities

Progress in the comprehension of the effect on light coherence in BRDF measurement with narrow spectral bandwidth and/or hight angular resolution have a direct impact on the scientific community because it questions the notion of BRDF itself. The work done to define the measurand for BRDF and BSSRDF has an impact for manufacturers of spectroradiometer, particularly for those who are developing image-based devices. Better control of BRDF leads to reduced Calibration and Measurement Capability (CMC) uncertainties at several participating NMIs, therefore improving the quality and the visibility of European metrology in the field of spectrophotometry. This work is already engaged with publication of papers claiming this reduction of uncertainties (see here). New primary facilities for the measurement of BTDF, BSSRDF and µBRDF have been constructed at several NMIs and will lead to new calibration services at NMIs. An important work of collaboration has been engaged with stakeholders to develop of new Certified Reference Materials (CRM), which will make traceability of BRDF, BTDF and BSSRDF more accessible to the European metrology community.

Impact on relevant standards

This project focused on the improvement and development of traceable quantities for the characterisation of the visual and optical properties of materials, which forms the terms of reference of CIE Division 2. The project impacted the work carried out in several CIE technical committees such as CIE TC2-85 (normalisation on BRDF), CIE JTC12 (measurement of sparkle and graininess) and CIE JTC17 (measurement of gloss). A reportership on the definition of BSSRDF has been opened by CIE (DR 2-86). Thanks to it the CIE international vocabulary has been extended by the project through the definition of BSSRDF. International metrology committees such as CCPR and EURAMET-TC-PR has been periodically informed about the progress of BxDiff. New calibration and measurement capabilities (CMCs) will be submitted on BTDF in short term and on BSSRDF on a longer term. As a consequence of this project, normalisation work on the measurement of BTDF and BSSRDF is foreseen.

Longer-term economic*, social and environmental impacts*

By providing new and reliable metrological references in spectrophotometry, this project improves the quality control of the appearance of objects and its virtual reproduction. The control of appearance is directly linked to the success and the competitiveness of goods. The project leads to improved rendering models able to better simulate the appearance of complicated objects. The uptake of outputs of the project will benefit computer generated imagery in movies and video games, digital prototyping of products, skin appearance rendering for medical and cosmetic industries, 3D printing, and energy assessment of buildings with glazing materials.

List of publications

1. A. Correia, P. Hanselaer, Y. Meuret, 2019, “Accurate and robust characterization of volume scattering materials using the intensity-based inverse adding-doubling method”, SPIE Vol 11057, https://lirias.kuleuven.be/2825988?limo=0
2. A. Calderón, A. Ferrero and J. Campos, 2020, “Accounting for polarization–related effects in the measurement of the bidirectional reflectance distribution function”, Metrologia 57(4), https://iopscience.iop.org/article/10.1088/1681-7575/ab804f
3. J. R. Frisvad, S. A. Jensen, J. S. Madsen, A. Correia, L. Yang, S. K. S. Gregersen, Y. Meuret, P.-E. Hansen, 2020, “Survey of Models for Acquiring the Optical Properties of Translucent Materials”, Computer Graphics forum (39)2, pp 729-755, https://diglib.eg.org/handle/10.1111/cgf14023
4. A. Ferrero, J. R. Frisvad, L. Simonot, P. Santafé, A. Schirmacher, J. Campos, and M. Hebert, 2021, Fundamental scattering quantities for the determination of reflectance and transmittance“, Optics Express 29(1), https://www.osapublishing.org/oe/fulltext.cfm?uri=oe-29-1-219&id=445047
5. P. Santafé-Gabarda, A. Ferrero, N. Tejedor-Sierra and J. Campos, 2021, “Primary facility for traceable measurement of the BSSRDF”, Optics Express 29(21), pp. 34175-34188, https://doi.org/10.1364/OE.439108
6. I. Santourian, T. Quast and A. Schirmacher, 2022, Uncertainty budget for PTB's gonioreflectometers and ways to improve it in the short VIS spectral range, Metrologia 59(2), https://iopscience.iop.org/article/10.1088/1681-7575/ac4e76

7. T. Labardens, P. Chavel, Y. Sortais, M. Hébert, L. Simonot, A. Rabal, G.Obein, 2021, Study and simulations of speckle effects on BRDF measurements at very high angular resolution, Electronic Imaging, 33, https://library.imaging.org/ei/articles/33/5/art00006
8. I Santourian, T Quast, S Teichert, K-O Hauer and A Schirmache, 2022, Novel LED-based radiation source and its application in diffuse reflectometry and polarization measurements, J. Phys.: Conf. Ser. 2149 012010, https://doi.org/10.1088/1742-6596/2149/1/012010
9. P. Chavel, Y. Sortais, T. Labardens, L. Simonot, M. Hebert, G. Obein, 2022, Advocating a statistical definition for the BRDF, Journal of Physics: Conference Series, 2149. https://hal-universite-paris-saclay.archives-ouvertes.fr/hal-03620283/
10. Z. Ma, P-E. Hansen, H. Wang, M. Karamehmedovic, Q. Chen, 2023, Harvey-Shack theory for converging-diverging Gaussian beam, JOSA B, https://doi.org/10.1364/JOSAB.478801
11. E. Molloy, P. Saunders, A. Koo, Effects of rotation errors on goniometric measurements, 2022, Metrologia, 59(2). https://zenodo.org/record/5842491
12. N. Basic, E. Molloy, A. Koo, Al. Ferrero, P. Santafé, L. Gevaux, G. Porrovecchio, A. Schirmacher, M. Smid, P. Blattner, K-O. Hauer, T. Quast, J. Campos-Acosta, G. Obein, 2023, Intercomparison of bidirectional reflectance distribution function (BRDF) measurements at in- and out-of-plane geometries, Applied Optics, https://opg.optica.org/ao/upcoming_pdf.cfm?id=486156
13. P. Santafé, 2020, Medida y transferencia de la unidad de BSSRDF, Master Thesis, Spain, https://digital.csic.es/handle/10261/226200.
14. F. Jinglin, Jeppe Reval F., Michael E., Tatjana Q., Alfred S. 2022. Preliminary Results of Angle-Resolved BTDF Characterization of Optical Transmissive Diffusers, Colour and Visual Computing Symposium 2022 (CVCS 2022). Identifier: urn:nbn:de:0074-3271-0, https://ceur-ws.org/Vol-3271/Paper13_CVCS2022.pdf
15. J.S.M. Madsen; R. Korhonen; P. Peltonen; O. Rodenko; S.A. Jensen. Nanostructure characterization and film thickness measurements at the fabrication line. “Nanomaterials: Applications & Properties” (IEEE NAP-2022), Krakow, Poland, Sep. 11-16, 2022. https://doi.org/10.5281/zenodo.7973545

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<table>
<tr><td colspan="2">Project start date and duration:</td><td>1 May 2019, 42 months</td></tr>
<tr><td colspan="3">Coordinator: Gaël Obein, CNAM   Tel: +33 158 808 788   E-mail: gael.obein@lecnam.net
Project website address: https://bxdiff.cmi.cz//</td></tr>
<tr><td>Internal Funded Partners:
1. CNAM, France
2. Aalto, Finland
3. CMI, Czech Republic
4. CSIC, Spain
5. DFM, Denmark
6. METAS, Switzerland
7. PTB, Germany
8. RISE, Sweden</td><td>External Funded Partners:
9. DTU, Denmark
10. Innventia, Sweden
11. KU Leuven, Belgium
12. UJM, France</td><td>Unfunded Partners:
13. CI, New Zealand
14. Labsphere, United States
15. Lucideon, United Kingdom
16. NCS, Sweden
17. SG, France</td></tr>
<tr><td colspan="3">RMG: -</td></tr>
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