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TABLE OF CONTENTS

1 Executive Summary

Introduction

A customer will often choose a product based on the way it looks. Consequently, many industries invest a large amount of time and money in developing sophisticated visual effects such as metallic paints, sparkle effects and matt finishes. Visual attributes such as colour, gloss, texture, transparency, sparkle and graininess all combine to give the appearance of a particular surface. To characterise and control these visual effects, companies currently develop a range of optical measurements for their particular product or rely on a human visual expert evaluation. This project developed standard measurement techniques to characterise surface finishes with traceability and lower uncertainty, so that industry can ensure reproducibility and compliance with specifications.

The Problem

Current standards and artefacts proposed by NMIs to industry to ensure traceability of measurements are very limited, and are insufficient for novel surfaces that show strong directional effects resulting from metallic, interference or diffractive pigments. New measurement methods, set ups and standards are required to provide the quantitative data that will ensure reproducibility and quality control of the new visual effects. For these new measurement methods to be taken up by industry, they need to be quick to make and easily interpretable. In addition, the methods should be highly correlated with the visual sensation of the human observer.

The solution

This project aimed to provide the measurement tools, methods and transfer artefacts to industry, to characterise modern surfaces and ensure traceability of measurement to the standard systems of units. The research must be carried out on a European level because the skills and equipment required is not present in a single country. A European effort that takes the lead in this area could give industry a competitive advantage by influencing research and development. Furthermore, standardisation from regional or international organisations such as the International Commission on Illumination (CIE) are important for encouraging adoption of new standards.

Impact

Outputs of xDReflect will not stay in metrological laboratories. St Gobain Research has used the high angular resolution bidirectional reflectance distribution function (BRDF) measurement set up by CNAM to characterize its new functional surfaces. A presentation of the measurement strategy and global colour estimation extrapolation for goniochromatic samples has been presented to coatings scientists of the company MERCK and BASF. The method developed for testing the colour difference on goniochromatic samples has been tested by Audi.

The first large comparison of primary goniospectrophotometer has been completed during the project and revealed where each participant of the comparison has room for improvement. Several institutes already updated their uncertainty evaluation. The data analysis also pointed out that reflection standards may show strong polarization dependence of the radiance. This observation lead to start working together on an investigation of the radiance polarization of various diffusely reflecting materials. A first model that relates the radiance's degree of polarization to the spectral radiance factor has already been advanced by MSL.

Work on developing and characterising new reference materials for fluorescence measurements has led to the development of a new type of reference material. The material shows more Lambertian angular fluorescence emission and reflectance profiles than currently commercially available materials. Furthermore, the characterisation process has led to the discovery of spectral changes in the angular profiles of reflectance for fluorescent material, which were earlier not known for such materials. The results will be relevant for quality control in industries where fluorescent dyes are used and will provide possible improvements in measurement uncertainties especially when non CIE geometries are used.

Partially driven by xDReflect results, Commission Internationale de l´Éclairage (CIE) has launch a new technical committee where outputs of the project will be used to progress on the normalization of the quantity.

2 Project context, rationale and objectives

Current standards and artefacts proposed to industry to ensure traceability of their measurements are limited to the visual effects they are able to generate. For example, in colour measurements, only two standard configurations, d:0 (diffuse irradiation and detection under 0°) and 45:0 (directional irradiation under 45° with subsequent detection under 0°), are approved by the CIE. This is insufficient and not adapted for all the novel surfaces that show strong directional effects resulting from metallic, interference or diffractive pigments. The situation is even worse for the other visual attributes like gloss where the standards have not evolved since 1978 or for fluorescence, where the measurement methods come from non-fluorescent materials and are today inadequate for application to fluorescent materials. There is the perception that the special-effects pigment industry and their derived sectors progress faster than the associated metrology standards.

Measurement of the optical properties of surfaces requires knowledge of its structure, its interaction with the incoming light, the possibility to measure the optical properties with at least the same acuity (spatial resolution) as a human observer, and the comprehension of how the human visual system uses the part of reflected light that comes in his eyes to encode and construct the visual attributes. None of these four issues are fulfilled in standard methodologies.

Different sectors e.g. automotive, cosmetics, paper, printing, packaging, coatings, plastics and steel industries develop products whose sale is highly influenced by the appearance. xDReflect aimed at meeting the demands of these industrial sectors to describe and control the overall macroscopic appearance of modern surfaces, which will strengthen their global competitiveness.

The research had to be carried out on European level, because the skills and background required to complete the project go from the mastering of fundamental optics to comprehension of the mechanism of human perception. Such a broad domain of competences at the highest level of expertise is never present in a single country. Furthermore, standardisation from regional or international organisations (e.g. CIE) and international agreement are highly important for the rather new field of appearance metrology.

In specific, the project dealt with the Goniochromatism, Gloss and Fluorescence properties of dedicated artefacts, which are the basis for future international standards with traceability to the SI-system.

2.1 Goniochromatism

Standard measurements in the classical field of reflectometry deal with the characterisation of materialised white, grey or colour standards, e.g. sintered PTFE, opal glasses, barium sulphate pellets or ceramic tiles, typically in standardised geometrical configurations, e.g. diffuse irradiation and detection under 0° (d:0°) or directional irradiation under 45° with subsequent detection under 0° (45°:0°). However, even for these so-called cooperative standard materials, the reflection behaviour is not only wavelength dependent but also varies strongly with the geometry. For new commercial instruments with extended multi-angle capabilities which are entering the market, in a recent verification of the spectral radiance factor extreme deviations of up to 385 % were observed. This effect might be even more dramatic for more complex standards which have specific features concerning angle and wavelength dependence. As a consequence, quality and production control based on these instruments might fail, leading to defective goods, low quality, and bad colour communication and inefficiency; also currently, it is possible that good quality products may be needlessly rejected. Thus, industry needs traceability, consultation and support for multidimensional, in- and out-of-plane reflection geometries. Diffuse reflectance is an important quantity for a variety of applications in optical metrology. Calibrations are realised for different industrial sectors such as the paper, textile and other coloration industries, companies producing radiometric and photometric instruments, as well as measurements for radiometric on-ground calibration of remote sensing instruments for space based applications on satellites. This is done by the measurement of absolute spectral reflection classification numbers in the desired geometries. For practical purposes, these measurements are predominantly accomplished relative to commercially available reflection standards. The measurement of the radiance factor β and the bidirectional reflectance distribution function (BRDF), respectively, in so called directed/directed geometries allow description of the optical properties of the material under test in user-defined lighting conditions. Nowadays, a measurement of the radiance factor β in the whole V(λ) spectral range from 380 nm to 780 nm in one geometry takes about 3 hours in order to achieve an uncertainty in the few parts per million range.

With a line scan (CCD) camera integrated into the current apparatus, this measurement will be possible within a few minutes, without increasing the measurement uncertainty. Taking into account the increasing number of standards and artefacts for the different types of modern surfaces, this improvement of measurements capabilities at the NMIs is mandatory. Furthermore, using photometric cameras, the spatial resolution is anticipated to be reduced from 20 mm to 20 µm. This will not only enable the investigation of the homogeneity of standards, artefacts and samples, but also makes it already possible to gain an insight on a microscopical scale into the structure. Finally, the implementation of new light sources (laser driven plasma light source, supercontinuum source) will lead to a significant decrease in the measurement uncertainty from nowadays approx. 1.2 % - 3 % to well below 1 % in the short wavelength range of the visible spectrum.

2.2 Gloss

Gloss is a visual attribute involved in the choice of an object that is recognised as the second most relevant beside colour, and is usually associated with quality and acceptability. The most popular device that quantifies gloss is the glossmeter. This instrument is based on the ISO 2813 standard and is useful in monitoring the day-to-day quality of a product, but is inadequate for many current requirements like describing the gloss level under different illuminations, or between two different colours or between two different materials like a velvet and a plastic. Psychophysical experiments that have been conducted to characterise the visual perception of gloss show that the specular gloss correlates with the sensation of gloss only at a first order. The glossmeter is clearly not adapted to characterise subtle effects such as manufacturers in the field of cosmetics are used to dealing with. The glossmeter is not adapted because the visual system extracts the gloss not only from the level of flux reflected in the specular direction but also from the shape of the specular peak itself.

To improve the comprehension of gloss perception, and to provide new measurement procedures more adapted to the need of the industry in the field of gloss measurement, such as cosmetics or the car painting industries, a better knowledge of the shape of the specular peak according the direction of illumination and to the nature of the material is required.

2.3 Texture

New texture effects namely sparkle (glitter) and graininess (coarseness) are growing in relevance within the automotive sector, and in the near future this will extend to other industrial sectors such as cosmetics, etc. New special-effect pigments, with metallic or interference or diffractive optical origin, and with various sizes and tridimensional shapes are very different to conventional pigments, in that they produce new and attractive visual effects in many coloured surfaces, as in the car bodies. The mathematical and optical algorithm for measuring and calculating the sparkle and graininess parameters of such pigments is currently an open question, although one multinational company has implemented and promoted the use of “texture values” in its colour instrumentation for the automotive sector.

Many unsolved questions are pending related to the viewing distance of sparkle in some measurement geometries, the influence of illuminance level, spectral power distribution of the light source, the discrimination versus detection tasks in the visual appearance of this new texture effect. In the same way the influences of optical parameters on graininess need to be understood, with particular regard to the use of diffuse illumination. These new texture effects, and gloss, are important in the visual discrimination of many materials, and few studies have been conducted to study the challenge of combining the contribution of colour difference (now related to many measurement geometries for goniochromatic materials) and the contribution of texture effects. The main purpose of many colouration industries, and specifically the automotive sector, is to have a reproducible and reliable method of assessing total visual appearance differences, which integrates colour and texture, and correlates with visual and instrumental data, for improving quality control of their products.

2.4 Fluorescence

In the field of fluorescence, most of the existing methods and standards for measuring functional materials have evolved from ordinary materials. However, the spectrophotometric measurement techniques used for these ordinary materials are inadequate for application to these modern functional materials. This is recognised by the fact that modern instruments for spectrophotometry which agree well enough on non-fluorescent materials show considerable disagreements larger than 5 % in measuring fluorescent samples. This has led some industries to purchase and use similar “conventional” devices in order to avoid inter-laboratory disagreements. As a result, the instrument industry has difficulties to develop instrumentation fulfilling the requirements of end users. In addition, there are concerns that the methods and results are not always comparable amongst different branches of industries. For example the fluorescent measurements in paper industry have to be comparable with printing technology, paint industry, and even in display devices technologies.

New types of reference artefacts needed for calibration and characterisation of instruments used for measuring fluorescence diffuse reflectance materials were identified within this project with the objectives to go beyond the state of the art by improving the 1 % uncertainties to as low as 0.2 % - 0.5 % in the measurement of luminescent radiance factor of fluorescence standards.

2.5 Data handling

The BRDF is given by a function $f_r(\theta_i, \theta_r, \phi_i, \phi_r, \lambda)$ which depends on the angular coordinates of the incident and reflected light as well as on its wavelength λ. For textured surfaces the BRDF has to be replaced by the bidirectional texture function (BTF) $g_r(\theta_i, \theta_r, \phi_i, \phi_r, \lambda, x)$ that depends also explicitly on the surface location x where the light is reflected. For translucent surfaces, the dedicated quantity is the bidirectional transmitted distribution function (BTDF) and the full measurements in the space are expressed in the bidirectional scattering distribution function (BSDF=BRDF+BTDF)! Those measurements lead to an enormous amount of data and often a lot of redundancy in the data that doesn’t facilitate the communication and the data analysis and is a restraint to the development in the field of goniorefIectometry.

The handling of this data needs to be addressed. The establishment of a formalism to select the opportune angular configurations, to organise and to manipulate efficiently the set of data acquisitions that represent the BRDF, the BSDF or the BTF measurements is urgent. The development of data driven models in order to reduce the amount of measurement data to a set of irreducible parameters that are the signature (or fingerprint) of the surface under test is urgently required.

2.6 Vision

In industries where the appearance of the product is crucial, i.e. car painting or cosmetics, the characterisation and the quality control of the product is still performed by a trained human observer. The ISO 9000 framework, however, requires that when it’s possible, the measurements have to be done in a more formal way, together with associated tolerances, to establish a formal quality-control system. Of course, this is more easily done using instruments because of their inherent controllability, stability and repeatability.

Nevertheless, for the industrials to use the instrumentation and methods developed in this project and switch from the traditional visual observation method to an instrumental method, it is essential that the measurements provided correlate to the perceptual response. The subject of the correlations between physical and perceptual measurands and the metrological evaluation of the uncertainties in the field of human perception were treated in this joint research project.

2.7 Objectives

The specific objectives of the project were to:

Improve primary goniospectrophotometers in order to progress in BRDF measurements and reduce the measurement uncertainty

1. Enhance the spectral and spatial resolution of reference goniospectrophotometers developed by each participant, using modern detectors, conoscopic optical designs, CCD cameras, line scan camera, modern light sources, etc
2. Reduce the measurement uncertainties on BRDF measurements by implementing modern detectors and modern light sources in the concerned facilities and validate the results by a comparison;
3. Improve the 1 % uncertainties to 0.2 % - 0.5 % in the measurement of luminescent radiance factor of fluorescence standards
4. Evaluate uncertainty and sensitivity coefficients for BRDF measurements and psychophysical measurements

Develop models for data compression, data representation and data handling for BRDF measurement

5. Reduce the total measurement time that is a significant restriction for calibration capacities
6. Reinforce the link with industry by creating a BRDF/BSDF public domain database for new advanced functional surfaces such as those used in the automotive industry
7. Propose recommendations for data handling of the large amount of data generated by BRDF measurements

Understand the correlation between the visual appearance and the BRDF

8. Improve in the comprehension and the definition of the visual attributes such as colour, gloss, sparkle, graininess, fluorescence, from a visual point of view
9. Correlate visual intensity and response stimuli to the advanced BRDF measurements, material characteristics (structural features) and environment attributes

Develop standard procedures and transfer artefacts in order to develop applied metrology for visual appearance attributes

10. Set the optimal geometries for colorimetric measurement of advanced surfaces like metallic colours, or sparkle/graininess effects and gloss measurement, in particular by the development and characterisation of advanced transfer standards
11. Propose a new standard and recommendations for gloss measurements that take into account the visual perception, the background and is adapted to modern surfaces
12. Propose new types of reference artefacts for calibration and characterisation of goniochromatism, gloss and fluorescence

In the following section, we report specific results according to the objectives of the project.

3 Research results

3.1 Objective 1: Enhance the spectral and spatial resolution of reference goniospectrophotometers

3.1.1 Development of a fully robot based goniospectrophotometer at CMI during the project.

The 7th primary full goniospectrophotometer in Europe, and the 12th in the world was developed at CMI during this project. The realization of this goniospectrophotometer was driven by the growing internal demand by the Czech industries for the metrological characterization of the appearance of new products and materials. In order to be able to provide this strategic service to the industry, CMI designed and realized a robot based goniospectrophotometer in its photometry laboratory in the outskirt of Prague. The facility shown in Figure 1 (left) is composed by a motorized circular ring 1.3 m external diameter to move the detection system around the sample, a 6 degrees of freedom robot to hold the sample, a monochromatic light source based on a High Intensity Laser driven light source coupled with a double additive monochromator and custom made detection system with 10 order of magnitude of dynamic range in the visible spectrum (from few fW to tens of μW) developed in collaboration with MSL. The facility is piloted with an in-house developed LabView software.

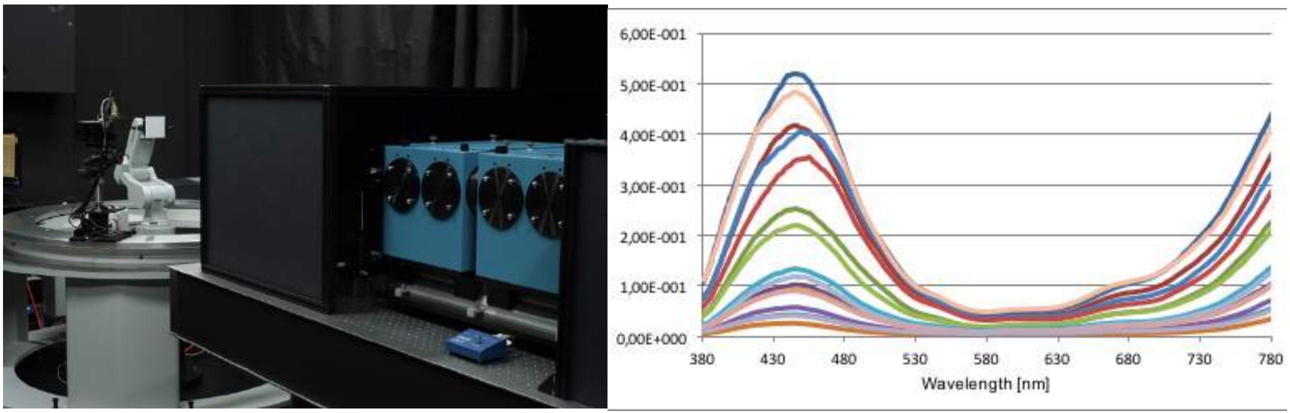

Figure 1. CMI goniospectrophotometer (left) and Spectro goniometric reflectance measurements made by CMI during the xDReflect intercomaprison (right)

The facility has been conceived to offer maximum flexibility. Due to 6 degree of freedom provided by the robot it can measure with both in plane and off plane goniometric configurations. Moreover the reflected signal from the sample can be measured using either a tunable monochromatic light in combination with a high sensitive custom made detector or using a collimated broadband light source in combination with a calibrated spectroradiometer. The CMI goniospectrophotometer performed a series of measurements on different set of samples for the intercomparison campaign in xDReflect. The samples were provided by the consortium and had to be characterized in a predefined set of goniometric configurations including off plane geometries. The results of these experiments are shown in Figure 1 (right).

Due to this work, in the near future CMI will be able to offer industry the complete BRDF characterization of traditional and new materials in almost any arbitrary goniometric configuration. This achievement has been greatly facilitated and efficiently implemented by the close cooperation and knowledge transfer with the other participants of the XDReflect.

3.1.2 Extension of the spectral range for BRDF measurements in UV and NIR

Because aerospace, terrestrial solar and industrial applications require knowledge of the BRDF function of various materials in the short wavelength (< 300 nm) and long wavelength regime (> 1700 nm), the spectral range for BRDF measurements was extended down to 200 nm in UV and up to 2500 nm in NIR.

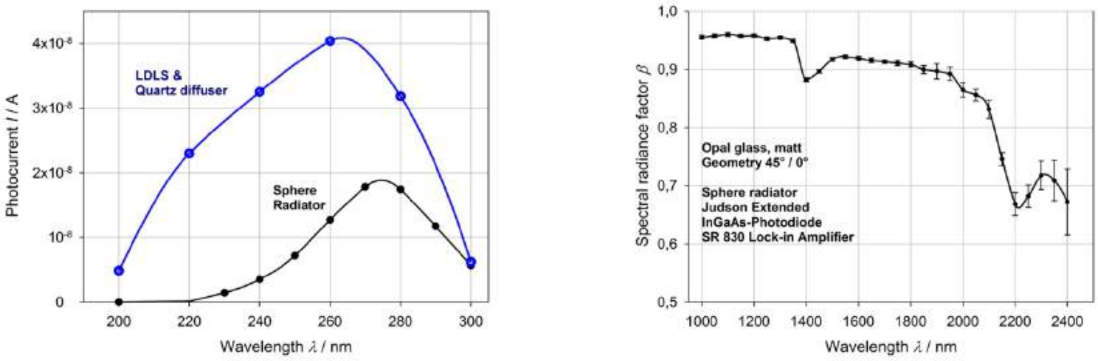

Figure 2 : Left, measured photocurrent for (LDLS & Diffuser) compared with that of the homogenous sphere radiator. Right, spectral radiance factor of an Opal glass standard in the NIR

In UV the problem of low radiation output faced when using classical thermal radiators like e.g. tungsten filament lamps was accounted for by introducing new concepts. At PTB the reference set-up was equipped with a so-called laser driven light source (LDLS). This laser excited plasma source is capable to generate short wavelength radiation above 190 nm up to the NIR with high radiance. In Figure 2 (left) the outputs of the LDLS equipped with a Quartz diffuser, optimized for the short wavelengths, and the usually used sphere radiator are compared.

The great improvement regards the available signal is clearly demonstrated. To generate the required homogenous radiation field at the sample a specific solarization stable diffuser had to be used. This effect, however, is also found in the samples to be calibrated. Therefore the search for new radiation stable standards is ongoing and extends beyond the XDReflect project.

In NIR the increasing noise-floor of the detectors can be circumvented by using lock-in techniques. In Figure 2 (right), we show the results of a demonstration measurements gained within in the project where the spectral radiance factor of an opal glass is depicted. This successful proof shows that the relevant technique is in principle available. Further improvements should be made and are in progress for the long wavelength end with respect to the achievable uncertainty. For the sake of simplicity a possible solution could be the use of the LDLS with its high radiance also for NIR measurements. This work has been presented in NEWRAD conference (A. Ferrero, C. Strothkämper, B. Bernad, T. Quast, K.-O. Hauer, J. Campos, A. Pons, A. Schirmacher, “BRDF variability of typical diffuse reflectance standards between 380 nm and 1700 nm”, Proceedings NEWRAD 2017, 240 – 41 (2017)).

Requests by e.g. aerospace sector are steadily increasing showing the need for traceable calibrations in the complete wavelength range from 200 nm to 2500 nm. The activities in the xDReflect project have provided a solid basis for an extended calibration service within the European BRDF community.

3.1.3 Development of an ultra-high angular resolution BRDF detection at CNAM

The initial objective for CNAM was to measure the BRDF of a surface with an angular resolution equal to the acuity of the human eye, 0.030°. In order to achieve such high angular resolution, it was necessary to control the divergence of the incident light beam.

ConDOR, on its illuminated system (Figure 3, left), uses a QTH (Quartz-Tungsten-Halogen) source (yellow) which image is formed on a pinhole (red) by means of a first lens (green). The pinhole has a diameter of 100 µm and it is placed at the focal of a doublet with a focal length of 400 mm (blue) which makes possible to have a beam of divergence 0.014°.

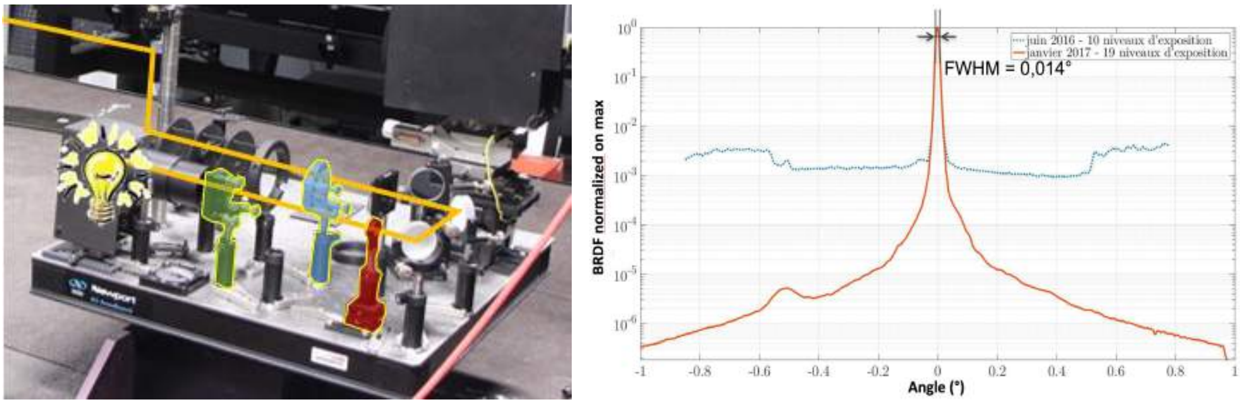

Figure 3 : Ultra high angular resolution of ConDOR setup (left): Illumination system: source is in yellow, lens is in green, pinhole is in red and doublet is in blue. Right: Cut of the apparatus function in the plane of incidence. The FWHM is 0.014°

Using a detection system based on a Fourier transform optic, it was possible to measure the light reflected with a theoretical resolution of 0.004°. The setup resolution is then the divergence of the incident beam. The theory has been verified experimentally. As shown on Figure 3 (right), the resolution of the system is 0.014°. This is the lowest resolution ever reached, allowing accessing the light reflected by the surface with the same acuity than the human visual system. This result led to progress in the field of gloss measurement and in the comprehension of gloss visual perception mechanisms.

The results have been presented through an oral presentation in NewRad conference (June 2017, Tokyo, Japan)

3.1.4 Conclusion

A fully robot-based goniospectrophotometer was developed during the project. The spectral range was extended from the visible range before the project, to include ultra violet and infra-red, opening the field of BRDF for aerospace and terrestrial solar applications. Results were validated by comparisons between project partners PTB and CSIC's BRDF measurements. Using a Fourier optic based detection system combined with a robot-based classical goniospectrophotometer an angular resolution for the BRDF measurement of 0.018° was achieved, which is the lowest resolution ever reached, This allowed access to the light reflected by the surface with the same acuity as the eyes of a trained industrial expert, which in turn led to progress in the field of gloss measurement and in the understanding of gloss visual perception mechanisms. A high dynamic CCD camera was implemented in three facilities, making it possible to study the sparkle effect in more detail.

3.2 Objective 2: Reduce the measurement uncertainties on BRDF measurements and validate the results by a comparison;

3.2.1 Development of a new low noise silicon based detector with a limit of detection below 2 fA.

BRDF measurements require a dynamic range in detection that has to be higher than 6 decades. On the MSL and CMI goniospectrophotometers, a single detection system must be able to measure the total incident flux on a sample and the flux scattered from the sample into the detector aperture in any given direction. Rather than introducing attenuation of the beam, the objective of this work was to design and build a detector that could make relative flux measurements over the many orders of magnitude required.

A hybrid photon detection system was designed to incorporate two sensors: a photon counter from Hamamatsu H11890 and an analog low photon flux detector (LOFD). The two sensors were mounted on a single 25 mm inner diameter integrating sphere into which the flux incident on the detection aperture is focussed. The detector was designed and constructed at MSL and tested at CMI.

The design of the detector is shown in the Figure 4. Light incident on the aperture is focused by the spherical mirror into the integrating sphere. The two sensors described above are mounted on the sphere and can be interchanged depending on the flux level being measured in order to extend the dynamic range of the system.

The detector was built at MSL and then tested at CMI by making measurements at a range of geometries on a glossy white ceramic tile. The relative uncertainties in signal were obtained over 7 orders of magnitude on the single sample (see Figure 4, right). These results show that the 3 mm Si diode can be used to calibrate the relative response of the photon counter at the upper limits of its flux range, and the photon counter can then be used to make low noise measurements for very low flux levels.

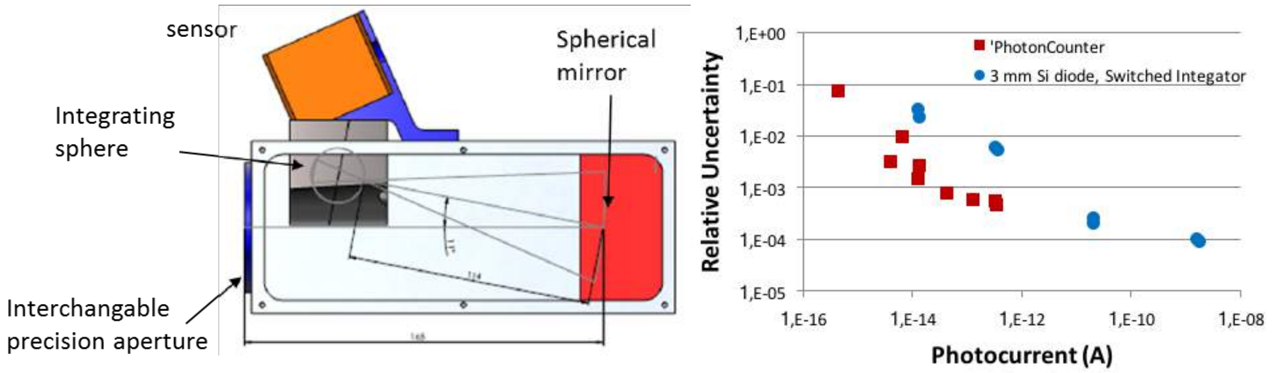

Figure 4 : Hybrid photon detection system designed at MSL and tested at CMI, able to reach a photocurrent up to 2fA. (Left): The design (Right): Relative uncertainties in signal obtained over 7 orders of magnitude on the single sample

Proof of concept for this type of hybrid detection system has been shown. This type of detector shows great promise for the improvement and extension of range of goniospectrophotometers, like those at CMI and MSL, making total flux measurements. This detector promises to be particularly useful for dark samples in which measurements of very low flux levels will be required. The results were presented at the 4th CIE Expert Symposium on Colour and Visual Appearance, September 6 - 7, 2016, Prague, Czech Republic (Koo, A, Porrovecchio, G, Smid, M, PP01 *Optical detection system for monochromatic beam goniospectrophotometry,* 4th CIE Expert Symposium on Colour and Visual Appearance, Prague (2016)).

3.2.2 Development of techniques for better characterisation of non-linearity and stray light effects on CCD detectors.

Glossy surfaces can show variation of their BRDF around the specular direction that can be higher than 6 decades. As several facilities existing inside xDReflect consortium use a CCD based detection, it has been necessary to find a way to access high dynamic measurement using CCD.

To achieve this objective, High Dynamic Range technique (HDR) has been set up to increase the dynamic of regular CCD. For metrological applications, it implies accessing the correction factors connected with the optical and thermal noise of CCDs, the flat field correction, and the evaluation of the linearity both in flux and time.

The thermal noise has been put negligible by cooling the CDD at -60°C using a Peltier element. The optical noise has been quantified with a 12 inch sphere and measuring the signal out of the detection field of view at different fluxes. The flatfield correction, that stands for local deviations in pixel quantum efficiency unwanted as well as effects from the optics (dust, marks, …), has been corrected using the same measurements, but inside the detection field of view. It has been found that this correction depends on the illuminated surface. The flux non-linearity is linked to the stability of the quantum efficiency as a function of its filling rate at a fixed exposure time. To test it, incoming flux has been varied to cover full dynamic range of the CCD for the same exposure time by means of a flux addition method. And finally, a work has been done to characterize the time-based non-linearity, which comes from the fact that the camera shutter has a finite shutting time. It has been shown that for exposure time smaller than 1.28s, a correction is requested and the measured flux is higher than the real flux. For exposure time higher than 1.28s, the correction is negligible.

To validate all these the corrections, measurement results over a Spectralon reference sample have been checked. A deviation of 3% with respect to the theoretical value has been observed, which is good given that ConDOR was not built to measure such diffuse samples.

3.2.3 First large comparison of reflectance factor measurement between 8 partners.

Inspired by existing systems at PTB and NIST, new BRDF facilities have been set up at different European NMIs during the last 12 years. By this the European infrastructure for such measurements and calibrations has been greatly improved. To assure comparability of calibrations a first large international comparison has been successfully performed among CNAM, CMI, CSIC, INRIM, MIKES, PTB and SP, and included also a non-European institute (MSL).

The comparison was performed in the visible spectral range on two sets of Ceramic colour standards purchased and calibrated by PTB and afterwards measured by the involved participants in two star-like calibration [20].

The first successfully performed large comparison for BRDF on diffuse reflection standards could only be carried out due to the fundamental work of the involved NMIs. The results show good overall conformity for most of the participants with respect the offered calibration service on BRDF. However, the comparison also revealed some particular problems to be addressed. Taking these into account, the European calibration service on BRDF will be further improved in near future as a result of xDReflect project. The results gained within the comparison have also been circulated to stakeholders and participants by supplying the calibrated sets to support their current BRDF developments.

3.2.4 First comparison of BRDF on glossy samples

Among the complete BRDF, visual gloss is principally related to physical reflection characteristics located around the specular reflection direction. This part of the BRDF is usually referred to as the specular peak. A good starting point for the physical description of gloss could be to measure the reflection properties around this specular peak. Unfortunately, such a characterization is not trivial, since for glossy surfaces the width of the specular peak can become very narrow (typically a full width at half maximum inferior to 0.5° is encountered). In result, new BRDF measurement devices with a very small solid angle of detection are being introduced. But differences in the optical design of BRDF measurement instruments may engender different measurement results for the same specimen, complicating direct comparison of the measurement results. This issue must be checked. BRDF measurements were performed on two samples, one being matte and the other one glossy, by use of two high level goniospectrophotometers with a different optical design and as such, a different instrument function. As shown in Figure 5, discrepancies were encountered for the matte as well as for the glossy sample. However, the discrepancies were much more important for the glossy sample, for which the BRDF function is smaller than the instrument function of one of the two used goniospectrophotometers. This finding was further exemplified by rendering luminance maps from the acquired BRDF data. Large visual differences were obtained, although both images were rendered starting from correct measurement data.

The results stress the need for knowledge about the metrological aspects of the measurement instrumentation when validating BRDF data. The comprehension of these parameters affecting the measurement results is an inevitable step towards progress in the metrology of surface gloss, and thus towards a better metrology of appearance in general. This work has been presented at Electronic Imaging conference in San Francisco in February 2015 and has been published in the proceedings (see G. Obein, J. Audenaert, G. Ged, and F. Leloup,"Metrological issues related to BRDF measurements around the specular direction in the particular case of glossy surfaces," Proc. SPIE 9398, Measuring, Modeling, and Reproducing Material Appearance 2015, 93980D (March 13, 2015); doi:10.1117/12.2082518).

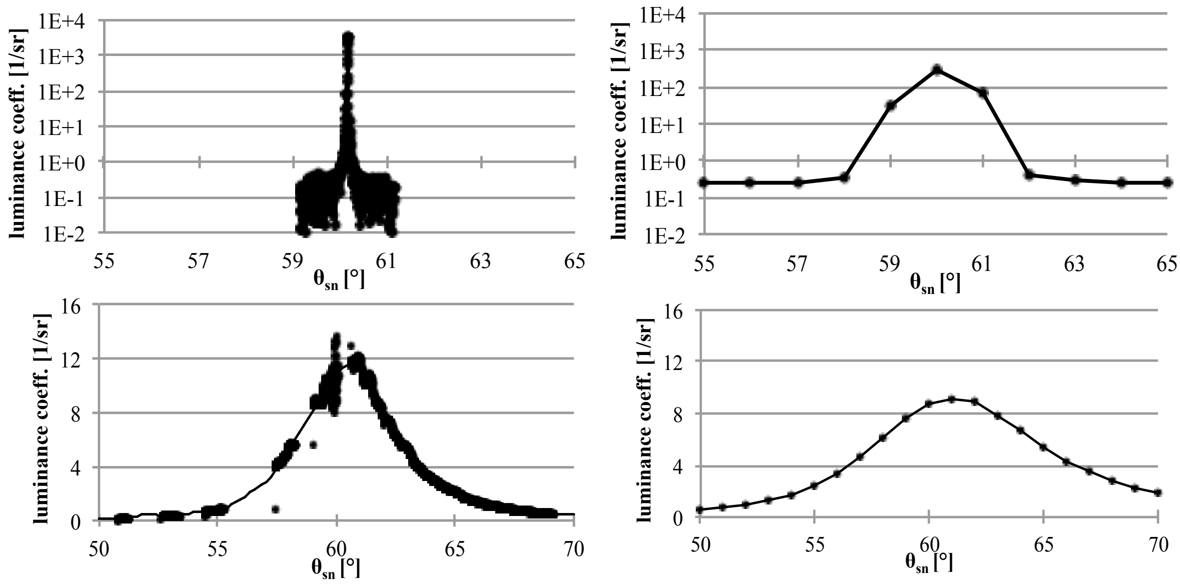

Figure 5: Comparison of the BRDF restricted to the area of the specular peak for 2 samples. Incidence 60°. Top, a matte sample. (Bottom), a glossy sample. (Left), measurements made at CNAM with a 0,026° apparatus function. Right, measurements made at KU Leuven with a 2,6° apparatus function. The BRDF value of both samples is influenced by the angular width of the apparatus function of the goniospectrophotometers.

3.2.5 First comparison of bidirectional bispectral luminescent radiance factor

Fluorescent brightening agents are used in various scientific and industrial applications to enhance the appearance of materials (e.g. textiles, paper and plastics). For accurate characterisation and reproduction of appearance, relative and absolute measurements of fluorescence characteristics are needed. Most of the existing methods and standards for measuring diffuse reflectance have evolved for non-fluorescent materials with the assumption of their near-Lambertian behaviour, however the angular emission and reflectance of fluorescent surfaces have been shown to deviate from Lambertian behaviour. The needs of the illumination and viewing geometries for calibrating the reference materials for fluorescence measurements vary between different branches of industry. Thus requiring calibration laboratories to provide traceability at several geometries.

The main aim of this work was to characterise the existing measurement facilities at VTT and CSIC to strengthen the traceability of fluorescence measurements of fluorescent diffuse reflectance standard materials and to reduce the uncertainty of the measurements.

The first known comparison of goniometrically measured bispectral luminescent radiance factors was done. Measurement performed were spectral fluorescence emission, absolute radiance factors and Helmholtz. Five pressed and sintered polytetrafluoroethylene (PTFE) based fluorescent diffuse reflectance standard materials were used.

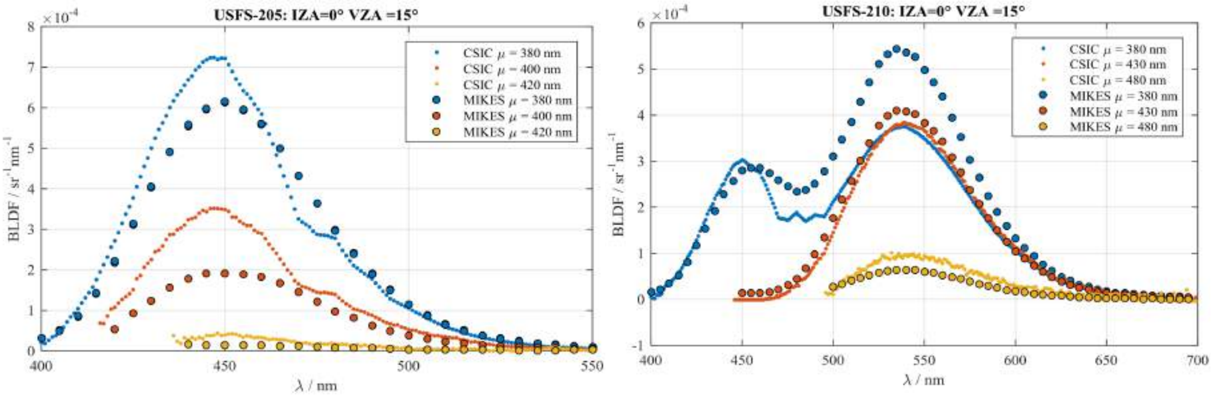

Figure 6: (Left): Emission spectrum of the sample USFS-205-020 illuminated at 0° zenith angle and viewed at 15° zenith angle. (Right): Emission spectrum of the sample USFS-210-020 illuminated at 0° zenith angle and viewed at 15° zenith angle.

Results, partially shown in Figure 6 for 2 samples, show that the emission peak is of the same order. However, it is hard to infer that the discrepancies are due to systematic errors, because the different sample were measured at identical conditions and no constant deviation between VTT (previously MIKES) and CSIC is observed. After investigation it appears that the discrepancy in the results come from insufficient relative responsivity calibration of the detection system, uncorrected polarising effects of the beam guiding optics, and insufficient bandwidth compensation.

All the details of this study, that provided essential information on the further development of instruments for fluorescent measurements, have been published in a 19 pages report. Results from this comparison have also been used for the Good practice guide for fluorescence measurements of solid surfaces by the two-monochromator method this study, published on xDReflect website.

3.2.6 Conclusion

In order to reduce the measurement uncertainty in BRDF measurement, a new low noise silicon based detector was developed, with a limit of detection below 2 fA, which extends the capability to measure dark samples. The total uncertainty was reduced on primary goniospectrophotometers thanks to the development of techniques for calibration of illumination/observation geometry and better characterisation of non-linearity and stray light effects on CCD camera detectors used in several NMIs.

The first comparison of reflectance factor measurements carried out by several different participants demonstrated that the BRDF is not as well controlled as expected, particularly for blue or red samples. It indicated where each participant had room for improvement and allowed better confidence in the uncertainty claimed. It also revealed that reflectance standard artefacts may show a dependence on light polarisation, which is important for progress on the comprehension of systematic effects in BRDF measurements. The same samples were measured with different commercial multi-angle spectrophotometers which showed that the control of the BRDF is about 5 times better at the NMI level than at industrial level.

3.3 Objective 3: Improve the uncertainty in the measurement of luminescent radiance factor of fluorescence standards

The colour of an object depends on the optical properties of the surface, the spectrum of illuminating source and also the observer. The colour can be defined by its tristimulus values, which, for a fluorescent surface, can be calculated for a desired source and an observer from the source independent bispectral radiance factor data: the Donaldson matrix. In order to measure the colour of a fluorescent surface accurately, accurate measurements of radiance factors are needed.

The linearity of the response of the CCD detector used in measurement of bispectral luminescent radiance factors at VTT has been characterised and corrected to within 0.5%. In addition,

- the stray light within the emission monochromator,
- the wavelength dependence of the dispersion of the grating,
- the polarisation effects and changes in the detection system responsivity induced by the fibre movement,
- the fluctuations in the irradiance on the sample,
- the wavelength mismatch for the monochromators, and
- the spikes in the CCD spectrum caused by external perturbations such as cosmic rays

Have been characterized and corrected for the radiance factor measurement process. Furthermore, the accuracies for setting the illumination and viewing geometries have been improved (see D3.1.1).

As a result of this correction work, the k = 2 uncertainties of measuring bispectral luminescent radiance factors with the VTT-Aalto goniofluorometer were reduced from 5% to 2.11-3.09% (depending on polarisation). The work has been published in measurement science and technology [9].

The improvement accuracy of measuring bispectral luminescent radiance factors has a direct impact on the quality calibration services that can be provided to industry.

3.4 Objective 4: Evaluate uncertainty and sensitivity coefficients for BRDF measurements and psychophysical measurements

3.4.1 Development of a virtual computer experiment to better understand uncertainties propagation in goniospectrophotometers

The measurement of the BRDF can be carried out with the assistance of robot-based gonioreflectometers. In order to gain insight into the measurement system, to enable a characterization of the whole measurement setup and to identify dominant uncertainty sources, virtual experiments can be used.

PTB have developed a simulation environment allowing to conduct virtual experiments emulating BRDF measurements of the real-life robot-based gonioreflectometer (Figure 7). The software consists of a set of interacting components, every part represents an entity with own methods and properties following the principle of modular software design. The software produces randomized errors of many relevant types and contaminates the simulated measurements with these errors. The program also does sensitivity analysis in a variety of forms and definitions, including perception-based metrics.

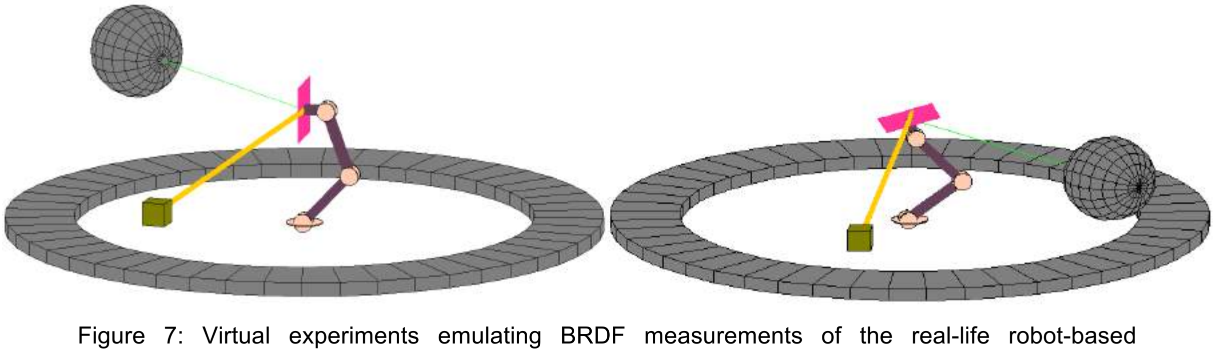

Figure 7: Virtual experiments emulating BRDF measurements of the real-life robot-based gonioreflectometer allowing the simulation of errors and the study of its propagation. (Left): for in-plane measurements. (Right): for out of plane measurement.

Small fluctuations of technical characteristics such as measurement angles or the robotic arm movements of the gonioreflectometer tend to lead to small fluctuation in BRDF measurements. On the other hand, it was possible to observe that occasionally there could be rather simple, even though noticeable, deviations in the measurement conditions, such that these deviations lead to complicated and unexpected shapes of the measured BRDF manifolds.

Virtual experiments, besides being very cheap, offer a number of advantages in research. In particular, one can emulate and check specific measurement devices, even without building them physically. Within the computer model, the current state of all parts of the virtual experiment can be easily controlled.

3.4.2 Creation of a new metric for quantifying BRDF distance based on mimicking human visual system

It is said that the appearance of surfaces can be sufficiently well characterized by the BRDF. However, standard statistical methods cannot be safely applied to BRDF data due to the nonlinearity of the data as well due to complicated and unexpected error structures of measured BRDF manifolds.

To allow comparison between BRDF, BRDF measurements have been considered as samples of points from a high-dimensional and highly non-linear non-convex manifold. It is argued that any adequate statistical analysis of BRDF measurements has to account both for the nonlinear structure of the data as well as for an ill-behaved noise. Standard statistical methods for the analysis of errors cannot be safely applied to BRDF data. A new class of measures of quality of fit for BRDF models has been constructed and it has been shown that the proposed distance measure leads to physically meaningful conclusions

The proposed distance metric has been constructed to reflect basic characteristics of human perception and leads to physically meaningful conclusions for BRDF data analysis. Basic properties of the new quasi-distances on the space of BRDFs have been analysed and the boundedness of these quasi-measures has been shown. Thus, the novel metric induces an absolute scale of distances on the space of BRDFs. This work has been presented at the World Congress on Engineering and Computer Science 2014 (Mikhail Langovoy, Gerd Wübbeler, and Clemens Elster, Statistical Analysis of BRDF Data for Computer Graphics and Metrology, Proceedings of the Vol II).

3.4.3 Methodology in line with GUM for the evaluation of CIELAB colour coordinate uncertainties.

CIELAB colour coordinates are characteristics of visible object's spectra widely used in colour science, and a reliable evaluation of the uncertainty associated with measured color coordinates is desirable. CIELAB colour coordinates depend nonlinearly on the tristimulus values, and the propagation of the uncertainty associated with measured tristimulus values to the colour coordinates is challenging.

Based on current guidelines for uncertainty evaluation in metrology given by the "Guide to the Expression of Uncertainty in Measurement" (GUM), two approaches have been provided for this purpose. One approach is based on linearization, .the second on a Monte Carlo method. Both methods were applied to a large range of scenarios representing different underlying spectra, varying size of uncertainties and degree of correlation.

In most cases, the simple procedure based on linearization yields almost the same results as the Monte Carlo method and, in viewing the latter approach as a reference, may safely be recommended. However, for large uncertainties of the tristimulus values, significant different results can be reached. In those cases, the Monte Carlo approach is recommended.

The approach based on linearization results in easily applicable analytical expressions for the uncertainty evaluation for CIELAB colour coordinates. However, the adequacy of the linearization ought to be checked and the proposed Monte Carlo method can serve as a reference method for this purpose. In this way, uncertainty evaluation for CIELAB colour coordinates in line with the current guidelines for the evaluation of uncertainty in metrology is warranted. This work has been published [19].

3.4.4 Conclusion

A virtual computer experiment was developed to allow a better comprehension of uncertainties propagation in goniospectrophotometers for special effect coatings and glossy samples. The experiment revealed that due to the high dimensionality of the BRDF, standard computation schemes used to evaluate the difference between two measurements are likely to be inappropriate for BRDF measurements. A new metric to access the distance between BRDF was developed and published, based on the evaluation of the difference in the "3D shape" of the BRDF, and mimicking what the visual expert does when comparing two different shapes.

Together PTB, CSIC and MSL developed a method for the evaluation of the popular CIELAB colour space, and the uncertainties. This is in line with the current guide to the expression of uncertainty in measurement (GUM).

3.5 Objective 5: Reduction of measurement time for BRDF

3.5.1 New methodology based on just 9 measurement geometries to characterize goniochromatic samples.

Special-effect coatings consist of a transparent medium containing traditional absorption pigments and flake-shaped effect pigments. The special-effect pigments have a selective reflectance due to their layered structure, which gives rise to interference. This produces a strong colour dependence on the illumination/viewing geometry and, in consequence, an appealing appearance (Figure 8). This colour effect is interesting for the automotive industry and for other applications such as packaging, cosmetics, and security inks. However, the complex way in which special-effect coatings reflect the radiant flux leads to some experimental challenges. To completely characterize the colour of these coatings under any illuminant and for any illumination/viewing geometry, the BRDF has to be measured at adequate measurement geometries to provide all information required to determine the variation of the spectral reflectance with respect to the geometry. Some sophisticated instruments to measure the spectral BRDF in an almost unlimited number of in- and out-of-plane geometries have been recently developed. However, industrial applications need more compact and fast systems for colorimetric characterization, and commercially available instruments have a limited number of measurement geometries, following guidelines from some international standards (ASTM, DIN, CIE, etc.). The potential of non-commercial and almost unlimited instruments is key to obtaining detailed BRDF measurements of special-effect coatings in order to obtain a better understanding of these special-effect pigments, coatings, and plastics composed by these instruments and to apply efficiently colour quality controls in industry. An open question is to determine the minimum number of measurement geometries required to completely characterize the spectral BRDF of special-effect coatings.

Figure 8 : Examples of goniochromatic coatings. The colour depends upon the direction of illumination and the direction of observation.

A reduced set of nine measurement geometries was proposed to estimate the colour of special effect coatings. A principal components analysis (PCA)-based procedure to estimate the colour of special-effect coatings at any geometry from measurements at a reduced set of geometries was tested in this work by using the nine proposed measurement geometries and those of commercial portable multiangle spectrophotometers X-Rite MA98, Datacolor FX10, and BYK-mac. The performance of the proposed PCA procedure for the colour-shift estimation for these commercial geometries has been examined for 15 special-effect coatings. Our results suggest that for rendering the colour appearance of 3D objects covered with special-effect coatings, the colour accuracy obtained with this procedure may be sufficient. This is the case especially if geometries of X-Rite MA98 or Datacolor FX10 are used.

The spectral BRDF of 15 special-effect samples have been measured with the gonio-spectrophotometer GEFE. These samples present a wealth of diversity in terms of angular variation in hue and chroma. A representative value of ΔEab, as averaged over samples and geometries with small aspecular angles, enabled us to determine the performance of colour shift estimation when using the available geometries of each of these instruments. As expected, due to its much smaller number of measurement geometries, the procedure showed the worst colour estimation when geometries of BYK-mac were used instead of those of X-Rite MA98 and Datacolor FX10, whose colour estimations were proven very good for some samples. This estimation performance was compared with the performance of a hypothetical instrument with only the nine measurement geometries proposed. The colour estimation was comparable with those obtained when using geometries of X-Rite MA98 and Datacolor FX10.

The colour estimation procedure evaluated here has great potential for various applications. For example, our results suggest that, for rendering the colour appearance of 3D objects covered with special-effect coatings, the colour accuracy obtained with this procedure may be sufficient. This is the case especially if geometries of X-Rite MA98, Datacolor FX10, or those proposed here are used. This work has been published [4].

3.5.2 Foundation of a mathematical framework to establish more efficient BRDF sampling

The BRDF is one of the fundamental concepts in such diverse fields as multidimensional reflectometry, computer graphics and computer vision. BRDF manifolds form an infinite-dimensional space, but typically the available measurements are very scarce. Therefore, an efficient sampling strategy is crucial when performing these measurements.

Simulation studies have been performed within a mathematical framework that allows to establish more efficient BRDF sampling and measurement strategies in the sense of statistical design of experiments and generalized proactive learning. To achieve this, the virtual gonioreflectometer simulation software has been extended in order to assess different sets of measurement geometries.

Several different sampling strategies for BRDF measurement have been analysed and compared for a wide class of loss functions including the novel perception based BRDF metric developed within this project. The simulation studies suggest that the default BRDF measurement strategy using a grid design is suboptimal.

This work has been published [23].

3.5.3 Conclusion

Normally, the characterisation of iridescence coatings requires extensive measurements because their BRDF strongly varies with the directions of observation and illumination. A new methodology based on just 10 measurement geometries was developed. Based on this restricted set of geometries and using a data analysis scheme, the user can assess the range of colours and appearances at all other geometries. This has the potential to drastically simplify the characterisation of special effect coatings. The same approach was attempted on gloss samples, but this was not successful, as it revealed that a new generation of BRDF models is required to characterise gloss samples.

3.6 Objective 6: Reinforce the link with industry by creating a BRDF/BSDF public domain database for new advanced functional surfaces such as those used in the automotive industry

There is a need for BRDF data by users from diversified fields like e.g. computer modelling, lacquer and coating applications as well as metrology. However, very often detailed results are only available to customers purchasing calibrations. Therefore, within the consortium it has been decided to make some of the results of xDReflect available to a broader public, to foster new developments.

The measurements have been made available through a dedicated space on the project website. This open access database of BRDF measurements is particularly useful for instrument manufacturers and the digital imaging and computer graphics community, who need real and trustable BRDF measurement data in order to test their new models of compression, rendering algorithms, or visualisation tools and devices. The BRDF data to be found apply only to specific samples but not to a material class. Detailed results can be downloaded in tabular form giving the BRDF for a variety of different geometries. (see http://www.xdreflect.eu/brdf-data/)

More than 60.000 users visited the website of xDReflect until spring 2017 to download results from the project.

3.7 Objective 7: Propose recommendations for data handling of the large amount of data generated by BRDF measurements

In the field of BRDF, work is required for the standardisation of the designation of goniometric reflection geometries. Even for the commonly used “in-plane” geometries there are a variety of notations in use in different areas of industry that inhibits the efficient exchange of information. For the emerging “out-of-plane” geometries there are currently no agreed notations available. Data processing standards for BRDF measurements is an important issue, since a large amount of data is obtained from such measurements. The complexity involving BRDF measurements is due to the four spherical freedom degrees to be controlled to reach every illumination/observation geometry plus its spectral dependency.

In accordance with CSIC and UA it was agreed to use a data format for representation of the measured BRDF data based on a 5D multiplicity. These are in detail four angular coordinates consisting of two angles in spherical polar coordinates defining the direction of the incident radiation and another two angles in spherical polar coordinates defining the direction of the reflected radiation. The fifth dimension is given by the wavelength of measurement. These data can be stored in a text-based CSV file which can be read from many evaluation programs. Using this operational frame, measurements are fitted to an analytical or phenomenological function. Afterwards, reflectance, transmittance and reflectance factors can be calculated for all illumination/observation geometries.

Standard formats are important to share, exchange and use BRDF data. This work is a first step towards the creation of database with measured BRDF data.

The foundation of a mathematical framework was built to allow new techniques to be applied to the statistical design of experiments and machine learning, in order to establish more efficient BRDF sampling and measurement strategies. A data representation algorithm for BRDF measurements in order to create a standard format of data files was established. The adoption of this universal file format by a large community of users is important to strengthen the communication between metrologist, instrument manufacturers and end users.

3.8 Objective 8: Improve in the comprehension and the definition of the visual attributes such as colour, gloss, sparkle, graininess, fluorescence, from a visual point of view

3.8.1 Development of light booths devoted to visual experiments on sparkle, goniochromatic and gloss

The measurement of a visual sensation is not a trivial operation. Because the measurand is in the head of the observers, no instrumental access is possible. The method to get the measurement value used “Psychophysical technics” that we can quickly describe as follows.

Different samples are presented to an observer, in a controlled environment and a simple question or action is asked. It might be a ranking, a pair comparison, or any other action in respect with the psychophysical protocol defined. The answers of the observer are recorded and from these answers, and using advanced statistics methods, a psychometric scale is derived and assigned to the samples. The construction of a full psychometric scale requests often many observers, and much repetition to make the statistics strong and convergent. In order to get accurate measurements, it is essential to control the environment. It must remain constant during the time the samples are shown, or from one observer to another, otherwise the psychophysical signal is blurred, and the data recorded will not be exploitable. This is the role of the light booth.

Dedicated light booths, adapted to the measurands, have been constructed within this project to realize visual experiment on sparkle and gloss.

For investigations on visual gloss, LNE-CNAM constructed a light booth (Figure 9, left) rigged with two types of light source, a diffuse background and a specular one. The diffuse lighting is achieved through six D65 fluorescent tubes installed on the ceiling of the booth, above a frosted diamond glass diffuser and a frosted Poly Methyl Methacrylate (PMMA) sheet. A mesh grid of characteristic length 5 cm is installed beneath the last diffuser. The specular lighting is originating from a 7-LED cluster located at the focal point of a condenser lens. A diaphragm restricts the angular width of the collimated lightbeam to 0.5°, corresponding to the angular width of the sun. This spot light is oriented towards the horizontal base of the cabin with an incidence of 45°. The light booth walls are covered by black curtains or “open space office like” decoration, according to the type of experiment. KU Leuven built a light booth (Figure 9, right) in agreement with ASTM D4449-15 standard. It is also a black cabin bearing a diffuse and a specular light source. A luminaire consisting of 2 uniform rectangular light sources, is denoted as the specular light source, is positioned 40 cm from the sample holder, with an incidence angle of about 60° toward the sample holder normal. In front of the light sources a rectangular mesh can be incorporated. An additional ambient light source, consisting of a series of fluorescent lamps placed behind a frosted plexiglas and further denoted as the background source, is positioned at the top of the viewing cabinet, at a distance of 1.25 m from the sample holder. This source generates a background illuminance, the value of which can be regulated.

Figure 9 : 2 light booths for accessing the visual sensation of gloss. Left, booth developed by CNAM has 2 possible configurations, “black” or “open space office”. Right, booth developed by KU Leuven.

For investigations on visual sparkle, INRIM developed four identical observation boxes (Figure 10, left) easy transportable to reach a larger number of observers. The samples lie on a plane whose inclination can be changed. The viewing directions are set up through three defined slots on a front shield, corresponding to the observation angles of 0°, 20°, 30. A last slot is made at the bottom for the observer to put the hands inside the box and arrange the sample on the plane. The lighting source is outside the box. Two boxes were covered by medium grey diffuse fabric and two with black diffuse fabric, as well the exhibition plane. It enabled to measure the effect of the background on the visual sensation.

Figure 10 : Light booths for accessing the visual sensation of sparkle. Left, 2 photos of the booths developed by INRIM (with samples on the exhibition plane and with the observation shield). Right, prototype booth developed by UA.

At UA, new lighting cabinet was developed (Figure 10, right) to analyze the sparkle and graininess models. This device allows to do evaluation of sparkle and graininess at different distances of observation and also at different geometrical configurations. In addition, it is possible to exchange the type of light source (different grades of color rendering) in order to know the influence of the color rendering of a light source on the visual appearance of the samples. This artifact was enclosed by black walls to avoid any reflections.

All the light booths developed for the project are now available in Europe for the study of the visual sensation. Because they have been developed specially for the purpose, i.e. visual gloss and visual sparkle, the psychophysical measurements obtained have been of high quality. These booths are for example at the basis of the “Guidelines for lighting arrangements to improve visual experience in exposition”, the “Guidelines for viewing cabinets for sparkle and graininess sample evaluation”, “Guidelines on the influence of the pigment particle size on the comparison of sparkle and graininess” and “Guidelines for new standard test method for visual evaluation of gloss”.

3.8.2 Proposal of threshold for colour tolerances and formulation for gonio-apparent colours

Colour formulation is an important topic in color technology since a good colour formulation allows a good colour reproduction to be obtained. Kubelka-Munk theory or the radiative transfer theory associated with two-, three-, and multi-flux approximations are commonly used to characterize colorants or pigments of a particular colour reproduction system (paints, textile, coatings, etc.) and to predict the final color recipe. However, these theories show some limitations when they are applied to effect pigments. Therefore, in xDReflect, we studied how Principal Components Analysis (PCA) can be applied for color formulation with these pigments of such a complex color characteristics.

Different effect pigments were considered to be calibrated by applying the PCA methodology considered a shade series are manufactured using the same process: nine blends were manufactured with the same absorption pigment (substrate) and the effect pigment in different concentrations.

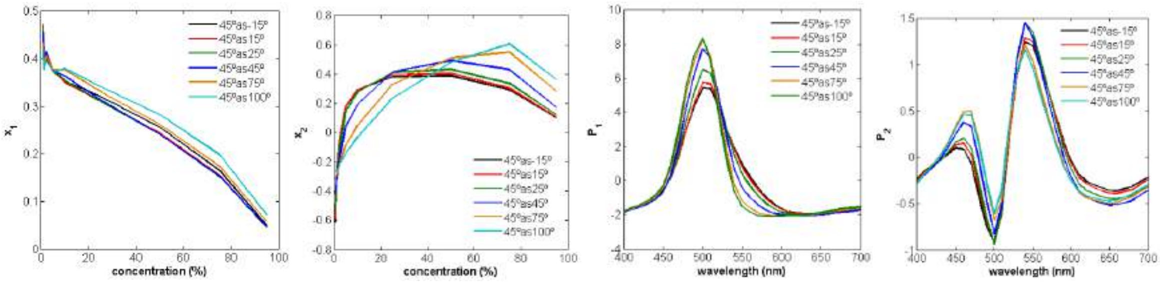

Figure 11 : Two first eigenvectors (left) and eigenspectra (right) from the pigment A for all the measurement geometries.

PCA was applied to the spectral data associated with each measurement geometry. The behavior for all the measurement geometry was quite similar. As example, it was found that the three first components are the most relevant ones since their cumulative variance is around 99.5 % for the most adverse case of a particular pigment (A). However, for other pigment (B), only two eigenvectors are required to explain a 99.6 % of the variance. By analyzing the obtained eigenspectra, it was identified that the first eigenspectra the first eigenspectrum represent the most important spectral feature of the effect pigment. The corresponding eigenvectors didn't show a clear tendency: for both pigment A and B, the eigenvector values increase with the concentration. However this variation was not linear, being dependent on the aspecular geometry. For the other eigenvectors, it was obtained a similar behavior. The lower the aspecular angle, the higher the contribution of effect pigments to the spectral reflectance, and at lower concentrations the spectral distribution of the coating begins to be more similar to the spectral distributions of pigments reflectance (Figure 11).

In order to apply this data for colour formulation, polynomials were fitted to the obtained eigenvectors and averaged spectral BRDF at every geometry. This way the spectral BRDF can be estimated for any concentration value. Thus, the first eigenvector and the average was fitted to a 4-order polynomial, however a 5-order polynomial was considered for the second and third eigenvectors by taking the logarithm of the concentration (log(c) vs. eigenvector 2). The polynomial equations fit quite well ($r2 \approx 1$) and the reconstruction is very similar to the original data for all the concentrations (Figure 12).

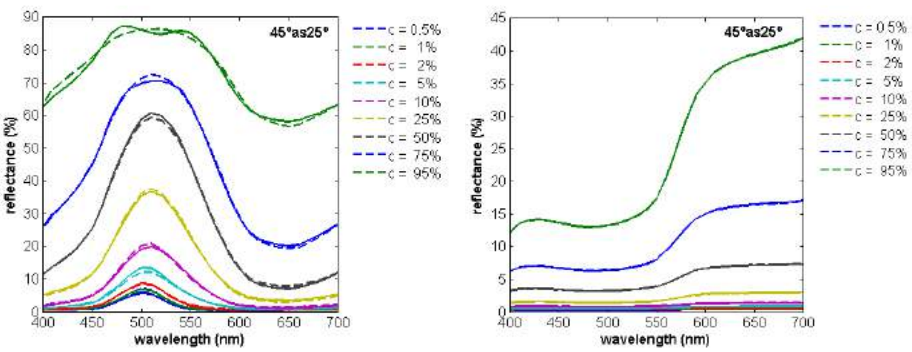

Figure 12 : Comparison of the reconstruction of the spectra data (solid line) and the original data (dash line) by using the polynomial equations (red line) for the 45° as 25° measurement geometry and the pigment A (left) and B (right).

To evaluate the goodness of the model, a colour difference was calculated based on the CIELAB color difference formula ΔE^*ab. For the measurement geometries far away to the specular direction, the results are better, however the colour difference for the measurement geometries close to the specular direction is greater than the previous ones. On the other hand, for low a concentration (c = 0.5%), the analytical model works worse than for high concentrations. The error, in average, was around 2 ΔE^*ab units for pigment A. The same analysis was done for pigment B. However, the error for pigment B by considering the color difference was smaller than for pigment A. The error calculated, in average, was around 0.25 ΔE^*ab units.

In conclusion, the results showed that this methodology could be very useful for colour formulation with special-effect pigments.

3.8.3 Comparison of visual performances for sparkle and graininess under LED and fluorescent lighting

The performances of LED lighting were tested for sparkle and graininess perception with subjective experiment based on local ranking of samples and comparison with measured values. 130 subjects were involved. The samples were illuminated with a zenith of illumination at 45°. A dedicated light both was designed allowing observations at 3 different angles (0°, 20° and 30° according the perpendicular of the sample) and one configuration called 45/open, where the angle of observation is not imposed to the observer. It has been demonstrated that

- the appearance of these new materials with special effects is influenced by LED technology, as was already proved for glare and colour rendering in literature
- the effectiveness of the measured values of sparkle intensity and graininess for different sources is very low. Sparkling and graininess are related to lighting source spectrum and his aspect must be taken in account in the measurement procedure.
- the effectiveness of the measured values of spectral reflectance factor and luminance for the assessment of brightness is very low. Integral detector are not able to resolve and differentiate particle shining from the background luminance and provides measurements with too low accuracy;
- no dependency on the level of adaptation was shown.
- the larger the particle size, the higher the perceived effect of sparkling (graininess);
- there is a strong dependency between ranking and dispersion with viewing condition. Measurement conditions are not well representative of natural behaviour (45/open). Specific viewing conditions are related to higher dispersion, and condition 45/open is always associated, for all samples and sources, to lower judgments dispersion and equivalence occurrence.

Fluorescent sources (Cold white and Warm white) are associated to a higher occurrence of equivalence in judgments, LED sources, especially the Cool one, have a lower rate of equivalence occurrence. Unfortunately LED sources are associated to higher discrepancies between objective measurement and perceived quality, especially when colour, brightness and glare are involved. CIE is aware of the problem and new calculation methods, as well new LED sources are on the way.

These results pushed INRIM to compare subject performances in qualities evaluation with and without Solid state lighting sources. The conclusion is that the use of LED in shops can be helpful to enhance the perception of sparkle and graininess. This work has been presented at the conference of Electronic imaging in San Francisco (2016) and the CIE conference on Lighting Quality and Energy effiency in Melbourne (2016) (P. Iacomussi, M. Radis, G. Rossi, « Brightness and sparkle appearance of goniochromatic samples”, Electronic Imaging, Measuring, Modeling, and Reproducing Material Appearance 2016, pp. 1-6(6), 2016, P. Iacomussi, M. Radis, G. Rossi, « Influence of LED lighting on colour evaluation”, CIE x042:2016, Proceedings of CIE 2016 Lighting Quality & Energy Efficiency, Melbourne, 2016)**.**

3.8.4 Evaluation of the influence of the shape and size of the light source on the sensation of gloss

Gloss is a visual attribute that plays an important part in the perception of the total appearance of a material. Gloss is implicated in the material identification, in the evaluation of the polishing level of the surface and is linked with the sensation of quality. But before trying to measure optically the gloss of a surface, it is essential to understand if the sensation itself is stable and what parameters can influence it. It has been shown that gloss is influenced by the colour of the surface. For instance, a black painting looks glossier than a white painting, even if the optical parameters are the same. At the opposite, visual gloss is not modified when the direction of observation of the surface varies, where the optical parameters are strongly influence by this type of modification. It has never been tested if gloss is influenced by the size of the lighting. Do we perceive the gloss of a surface identic when we observe that surface under a cloudy sky and under a sunny sky? This information is important because according to the answer, it might influence the design of future gloss measurement instruments.

A psychophysical experiment was sat up to answer this question. The protocol chosen was a pair comparison, the results of which were processed by a Maximum Likelihood Difference Scaling algorithm. 16 observers twice evaluated 35 key-sample quadruples made from 7 grey samples presenting a gloss level varying from very matt to very glossy. The experiment lasted from 30 to 40 minutes per observer. Measurements were carried out in a black light booth that has been described above (see subsection 3.8.1) under 2 lighting conditions. One was simulating a cloudy sky. The other was a simulation of a sunny sky.

The results are shown on Figure 13. The sensation is plot against the gloss measurement accessed with a glossmeter in the 60° configuration. The full scale is normalized to 1 in both configurations. It is possible to see that the sensitivity of the visual system, which is the slope of the curve, is lower in the matt area (gloss index <40) under a diffuse lighting than under the specular lighting. In the glossy area (gloss index > 60), the sensitivity is similar.

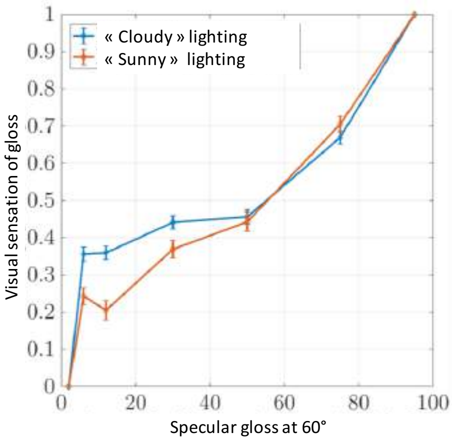

Figure 13 : Evolution of the sensation of gloss according to the specular gloss index (60°) for 2 different lighting conditions: Under a diffuse lighting that simulates a cloudy sky and under a specular lighting, that simulates a sunny sky. Only for matt samples, the sensitivity is influenced by the lighting conditions.

This experiment proved that geometrical organization of the lighting has an influence on the perception of gloss only for mat surfaces. In this region, the observer is more performant when lighten under a sunny sky than under a cloudy sky. For the glossy surface, the type of illumination doesn't matter. This information is important. It allows to understand better how the visual system works when performing visual gloss evaluations.

3.8.5 Evaluation of the influence of the environment on the sensation of gloss

Humans evaluate the gloss of objects daily because gloss contains information on the material they are looking at. But gloss also plays a role in the identification of the shape and of the curvature of objects. It is possible that gloss might be also implicated in other cognitive processes like for example the identification of shape, position, luminance and spectrum of the light source. So, in that sense, gloss is not just a visual attribute, it participates to the construction and identification of the full tree dimensional environment of the observer, and it gives it coherence and unicity.

Currently, most of the perceptual evaluations of gloss are performed according to ASTM D4449 standard ("Standard Test Method for Visual Evaluation of Gloss Differences Between Surfaces of Similar Appearance"), which recommends the use of a full black environment and a unique light source. It might be questionable whether it is appropriate to put observers in a black environment to perform a task of gloss rating, where they do it usually in a complex environment.

A psychophysical experiment was sat up to answer this question. The protocol chosen was a pair comparison, the results of which are processed by a Maximum Likelihood Difference Scaling algorithm. 20 observers twice evaluated 35 key-sample quadruples made from 7 grey samples presenting a gloss level varying from very matt to very glossy. The experiment lasted from 30 to 40 minutes per observer. Measurements were carried out using the 2 different lightings. The experiments have been performed in a black environment and in a “complex” environment that has strong cognitive clues. For this last, we chose an “open space office desk” environment. The 2 ambiances can be seen on Figure 9.

For the cloudy sky lighting, results show that the sensitivity of the observer is equal or better on all the gloss range (the reader should make abstraction of the first segment in the graphs, that shouldn’t be taken into account). Same remark can be done for sunny sky lighting.

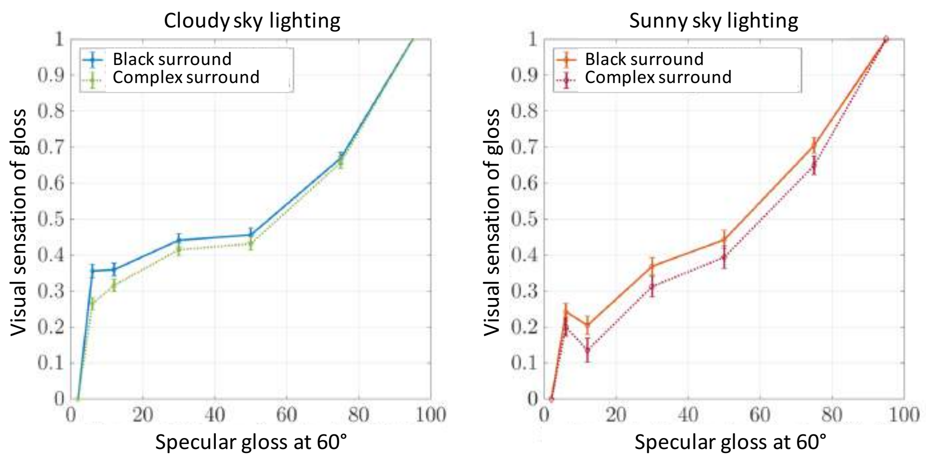

Figure 14 : Evolution of the sensation of gloss according to the specular gloss index (60°) for 2 different lighting conditions. Left: Lighting that simulates a cloudy sky. Right: Lighting that simulates a sunny sky. Under each lighting, the experiment was done in a black environment and in a complex environment.

These results show that the visual perception of gloss is influenced by the environment under which the task is performed. The “office” ambiance increases the sensitivity of the observer. This result is in agreement with previous studies made using virtual images. It traduces the fact that observers are able to find cues in the reflected highlights that come from the environment when they evaluate the gloss of an object.

This result is important for industries who work with observer panels because it will allow them to enhance the sensitivity of the panel.

3.8.6 Conclusion

Light booths were constructed and delivered for visual experiments on sparkle, iridescence and gloss visual effects. Based on visual experiments and a principal component analysis, a threshold for colour tolerances and formulation for gonio-apparent colours was produced. This is important for the automotive industry because it puts a limit below which no effort is requested in painting or retouching work and is directly linked to monetary savings.

Visual experiments made on gloss and high gloss samples have shown that the perception of gloss is not dependent on the shape and size of the light source, the observer sees the same level of gloss under either a cloudy or sunny sky. This is not true for mid-matt and matt samples, where sensitivity is better under a “sunny” illumination. In the entire gloss range, the sensation is enhanced when the samples are presented in a natural environment rather than a full black room. This result is important for industries who work with observer panels because it allows them to enhance the sensitivity of the panel. The project also determined that it would be possible to develop “gloss metrology” based on the experience of a “standard observer”.

3.9 Objective 9: Correlate visual intensity and response stimuli to the advanced BRDF measurements, material characteristics (structural features) and environment attributes

3.9.1 Correlations between sparkle sensation, particles characteristics, illuminance level, geometry of illumination and colour rendering index.

The sparkle attribute can be easily recognised, categorised and scaled by subjects, however, it is not well described in metrological terms, or even by subjective perception. The aim of this work was to investigate how visual environmental conditions (i.e. level of illuminance, level of adaptation, spectral composition of light) and particles characteristics (pigment size, pigment shape) affect the perception of this visual attribute.

Different visual experiments were carried out to evaluate the texture effect. The psychophysical method used was the method of adjustment. In this case, the subject must adjust or manipulate freely the intensity of the stimulus (sparkle) until it is able to perceive it or to stop perceiving it, by adjusting the distance at which the texture effect is detected. Six evaluations per sample were done by each observer, three replications in which the observer was moving away from the sample and three in which the observer approached the sample to detect sparkle.

One experiment consisted of 18 samples divided into two sets, nine chromatic metallic samples (silverdollar) and nine achromatic metallic samples (cornflake) with different average sizes (D50) between 9 and 35 µm. In this experiment, it was proved that statistical design of experiments (DoE) is applicable to visual appearance of materials. In this case, structural data (D50, shape) were studied versus detectability. A first conclusion is that pigment size (D50) is more important than shape. On the other hand, Silverdollar is more easily detectable than cornflake. The interaction between shape and size was identified and evaluated by obtaining a 2nd - order multiple regression model (Figure 15, left). Finally, an exponential growth modelling d = f(sparkle value) is valid for instrumental correlation (Sg).

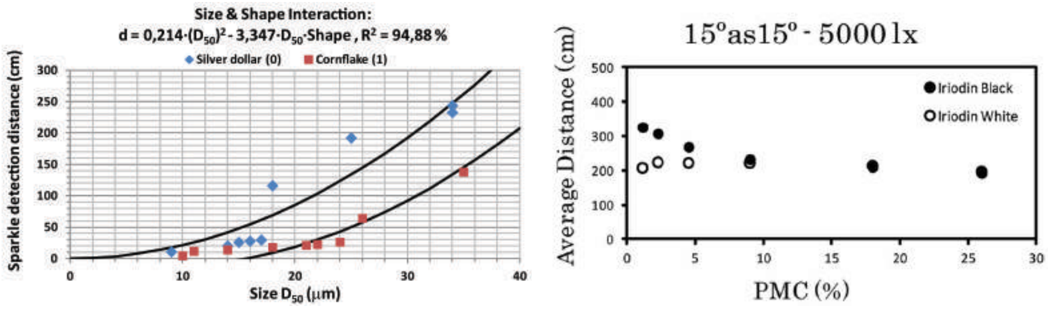

Figure 15 : Left: Regression model for size and shape interaction. Right, Iriodin Pigment Mass Concentration (PMC) vs Average Distance`

3.9.2 Definition of perception threshold of sparkle and graininess according to the distance of observation

In one experiment, 18 samples were used with different special effect pigments: Hydrolan (6), Iriodin (6) and Xirallic (6). The concentration of the special effect pigment was: 1.13, 2.25, 4.5, 9, 18 and 26%. The results (Figure 15, right) show that if the pigment concentration increases, the detection distance decreases. This fact is more noticeable for the black background, although this tendency is also found in the white background. On the black background the same trend was obtained, that is, higher pigment concentration, lower sparkle detection distance. On the contrary, on white background, with increasing pigment concentration on the sample, the observer can detect sparkle at more distance, but always shorter than that for black background. As conclusion, depending on the background colour, two behaviours are obtained.

In another experiment, two light sources were selected: a warm LED lamp with a 3200K color temperature and a daylight LED lamp with a 6500K color temperature. For each lamp, different illuminance levels were considered: 800, 2400 and 5000 lx. The evaluation was performed in three different measurement conditions: 15ºas15º, 45ºas45º and 75ºas75º. The analysis of the results was conducted by using the statistical design of experiments: 3221 multilevel factorial design was selected taking into account the involved factors (CCT, illuminance level and measurement geometry) and the number of levels for each factor. It has been concluded that the sparkle texture effect is detected at a greater distance for low illumination levels and for the 45ºas45º geometry, besides the color temperature does not influence significantly.

This work has been communicated at the 4th CIE Expert symposium on Colour and Visual Appearance, (Prague 2016), XI Congreso Nacional del color (Ourense 2016) and that the 23rd Color Imaging Conference (Darmstadt, 2015). For each event, an article has been published in the proceedings (Gómez et al. Analysis on the interplay of the pigment shape and size on sparkle detection distance by design of experiments. 4th CIE Expert symposium on Colour and Visual Appearance. Prague (2016), Gómez, O. et al, Correlations between concentration of effect pigments, optical, measurements and visual assessment of sparkle. 4th CIE Expert symposium on Colour and Visual Appearance. Prague (2016), Gómez et al, Implementación del diseño de experimentos en la detección visual del sparkle. XI Congreso Nacional del color. Ourense (2016), Gómez et al, J. Influence of the Effect Pigment Size on the Sparkle Detection Distance. 23rd Color Imaging Conference (CIC23). Darmstadt (2015))

3.9.3 Correlation between sparkle visual sensation and the actual commercial instrumentation

Today, only one instrument exists on the market to measure the effects of sparkle, the multi-angle spectrophotometer BYK-mac. Through a psychophysical experiment, we established the relation between the visual sensation of sparkle and the instrumental sparkle texture effect indexes, named Sparkle grade (Sg), Sparkle intensity (Si) and Sparkle area (Sa). The objective of this work was to see if a linear correlation exists between these indexes and the sensation.

A visual experiment was designed based on the method of magnitude estimation. Observers are asked to assign numbers in proportion to the magnitude of a stimulus taking into account two references (anchors): a reference sample without sparkle (0) and other reference sample with high sparkle (10) (Figure 16).

Figure 16 : Left: the observer performing the psychophysical experiment. Right: Picture of the 2 anchos, with the mask used for the magnitude estimation

4 sets, giving a total of 92 samples with metallic and interference pigments from different suppliers were used. The main characteristics are described below:
Set 1: Merck® and JDSU® pigments (Iriodin 9221, 9225; Colorstream T20-01, T20-04; Chromaflair 330)
Set 2: Eckart® Al pigments
Set 3: BASF Coatings (Variocrom®)
Set 4: Eckart: Luxan® (synthetic mica)

The correlation between the sparkle magnitude assigned by observers and the sparkle magnitude calculated by the instrument was studied (Figure 17). It was found that sparkle grade (Sg) correlates very well with human visual perception. The performance is slightly better for 15ºas15º measurement geometry than for 45ºas45º measurement geometry. However, there is no significant differences between 800 and 2400 lx. The Sparkle intensity (Si) and sparkle area (Sa) do not correlate well with visual perception for any measurement geometry and any illumination level. This failure has happened because the psychophysical experiment was designed to evaluate the sparkle grade and not to evaluate the two independent variables.

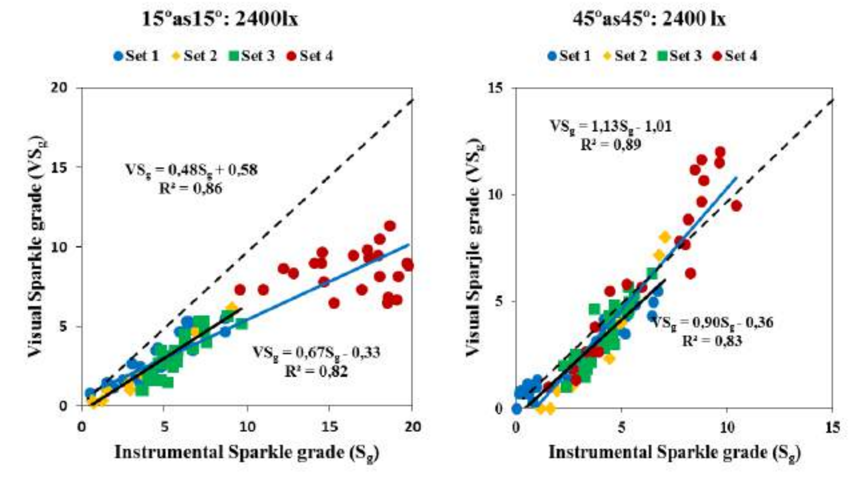

Figure 17 : Sparkle grade correlation for high illumination condition (2400 lx) for the 15ºasº15º and 45ºas45º measurement geometries

This research enabled to evaluate the only commercial system allowing the measurement of sparkle stimuli. It was established the need to carry out a deep study to define the mathematical and optical algorithms allowing the characterization of the sparkle attribute. This work has been published [13] and has been presented in two conferences (Perales, E.; Chorro, E.; Gómez, O.; Viqueira, V.; Martínez-Verdú, F.M. Estimation of the sparkle texture effect by visual and instrumental assessments. 4th CIE Expert symposium on Colour and Visual Appearance. Prague (2016); (Perales, E.; Chorro, E.; Gómez, O.; Viqueira, V.; Martínez-Verdú, F.M. Estimación del efecto de textura de colores goniocromáticos mediante evaluaciones visuales e instrumentales. XI Congreso Nacional del color. Ourense (2016)).

3.9.4 Comparison of independent perceptual gloss scales to initiate the work on a "gloss standard observer"

The total visual appearance of a surface is a concern in a wide panel of industrial sectors. In many manufacturing processes, more than instruments, the visual system has the last word when quality of the finished product is at stake. Psychophysical studies aim to produce scales describing our perception of stimuli. In the field of gloss appraisal, such techniques are used since Hunter early works and many scales describing this quantity have been produced. However, to our knowledge, no metrological assessment of scales constructed from a same set of samples through different protocols has ever been carried out.

In this work, psychometric functions have been compared, determined with different protocols and set of observers in resembling environment, over a same set of commercial glossy samples.

One experiment was carried out by CNAM, using the light booth developed at LNE–CNAM in the black environment and the "sunny" lighting (see subsection3.8.1, for details). The psychophysical protocol was a pair comparison, the results of which are processed by a Maximum Likelihood Difference Scaling algorithm. 16 observers below 40 years old (8 males, 8 females), evaluated 35 key-quadruples. The paradigm they had to answer was "which pair exhibits the higher differences among its samples?" The experiment lasted from 20 to 40 minutes per observer.

The second experiment was carried out by KU Leuven, using light booth developed at KU Leuven, which was built according to ASTM D4449-15 standard. It is also a black cabin bearing a diffuse and a specular light source (see subsection 3.8.1, for details). The psychophysical protocol was a paired comparison technique according to a method described in the literature. 16 observers (8 males, 8 females), aged between 18 to 40, were asked to rate the difference in visual gloss between each pair of two samples, on a -3 to 3 scale, in both orders of presentation (left vs. right). The presentation order was defined by a Diagram-balanced Latin square. For each observer, the experiment took between 30 to 40 minutes.

The same samples have been uses for both experiments. It was the seven dark grey samples from NCS gloss scale. They are made from coated paper and exhibit the same hue. Each one was glued on a glass support for KU Leuven and on a plastic one for CNAM. Their 60° specular gloss levels range from 2 gloss units to 95 gloss units. The size of the samples was 50x80 mm.

For each laboratory, we obtained a psychometric scale and compared the scales. A good agreement is found between the 2 scales (Figure 18).

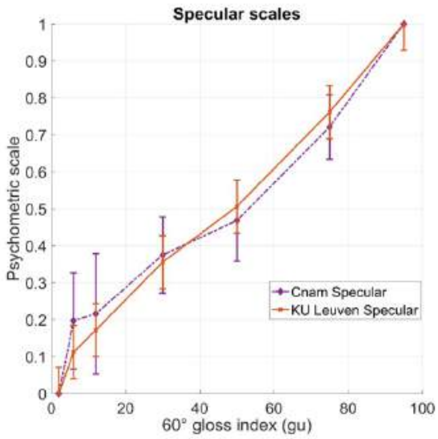

Figure 18 – Comparison of the gloss psychophysical scales. Scale have been measured at KU Leuven and CNAM, using the same samples and a similar environment, but different protocols and different observers.

As a conclusion, the first intercomparison of psychometric scales describing gloss perception was carried out between two laboratories. It demonstrated a good agreement for the scales measured in a specular ambient. If a standard observer for gloss needs to be described, one should keep in mind this result. An extension to this work will be to derive further scales in different environment. We should also use different protocols to treat our results and gain more insight on them. This work has been present at the 4th CIE international symposium on visual perception in Prague 2016 (Ged. G, Leloup F., De Wit Y., Obein G., “Intercomparison of visual gloss psychometric scales”, Proceedings of 4th CIE Expert Symposium on Colour and Visual Appearance, Prague, CZ, CIE x043:2016, Sept 2016).

3.9.5 Conclusion

Correlations between sparkle sensation and particles characteristics have been identified according to the illuminance level, the geometry of illumination and the colour rendering index. The comparison of visual performances under LED and fluorescent lighting associated with the visual experiments on perception threshold of sparkle and graininess according to the distance of observation, provided important information on sparkle visual effect. LED lighting was adapted to show the effect. For pigment manufacturers the work provides a structure for new effects, and for instrument manufacturers it provides information on what matters visually in this effect, which is essential information if you want to measure and reproduce the visual effects.

An intercomparison of psychometric scales describing gloss perception showed that it would be possible to develop “gloss metrology” based on the experience of a “standard observer”.

3.10 Objective 10: Set optimal geometries for colorimetric measurement of advanced surfaces visual effects by the development and characterisation of advanced transfer standards

3.10.1 Set up of two new measurement lines for the measurement of sparkle and graininess

When effect coatings, widely used in automotive industry, are illuminated by a highly directional source as the sun on a clear day, a non-uniform texture is observed consisting of very bright spots distributed on a dark surround, an effect usually known as sparkle, glitter or glint. It is produced by the mirror-like metallic or interference pigments in these coatings, which are not perfectly horizontal with respect to the coating surface. Then, for given illumination and viewing directions, just a small number of pigments (sometimes referred as flakes) will specularly reflect light towards the observer. The characterization of this effect is commercially important e.g. for the automotive industry because a high percentage of cars with effect coatings are sold. The present technological state of the imaging technology allows this effect to be measured, but the only commercially-available instrument able to quantify sparkle is the so-called BYK-mac®, which provides three geometries of directional illumination (15°, 45° and 75°), one geometry of diffuse illumination and a fixed viewing direction at 0° with an imaging system. Sparkle and graininess parameters are obtained by this instrument (graininess is the perceived contrast in the light/dark irregular pattern exhibited by effect coatings viewed under diffuse illumination conditions). These parameters supposedly are well-correlated with the visual experience. However, the measurands corresponding to these parameters are not clearly defined and they cannot be measured by any other instrument.

CSIC and PTB have developed two independent instruments to measure sparkle and graininess at almost any measurement geometry, and not only at those provided by BYK-mac.

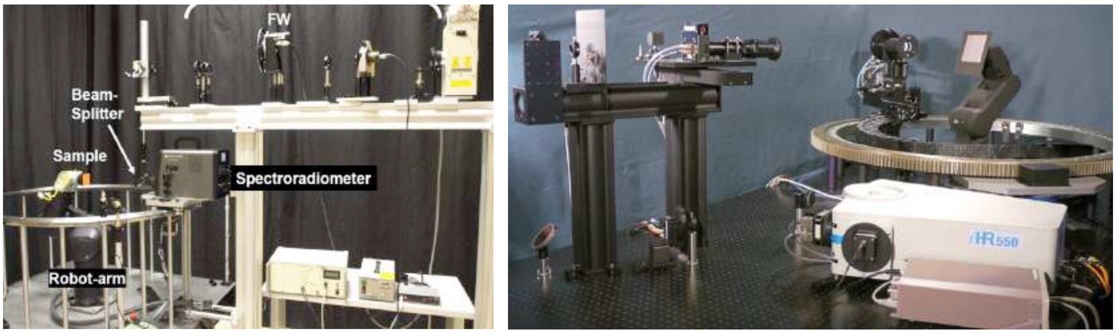

Figure 19 : Photo of the two goniospectrophotometers that has been equipped for sparkle measurement. Left, GEFE at CSIC. Right, ARGon3 at PTB.

GEFE (CSIC’s goniospectrophotometer, shown in Figure 19, left) was upgraded with a CCD camera (Qimaging, Rollera XR) as detector to provide the acquisitions with spatial resolution. The dynamic range of the camera is 12 bits, the detector size is 695 × 520 pixels (2/3″) and the pixel size 12.9 µm × 12.9 µm. An AF NIKKOR 50 mm f/1.8D lens objective was used. GEFE allows bidirectional reflectance to be measured in the visible range at any geometry, including out-of-plane and retro-reflection directions, with an illumination solid angle with a half-angle of 0.5°. No absolute calibration was required, since the measurands were independent on absolute photometric quantities. For a similar reason, we did not attempt to correct the non-uniformity of the camera response. By evaluating the relative responsivity of the pixels (net response by integration time at constant radiance) at different integration times, it was estimated that non-linearity introduces an uncertainty of less than 2% in the measure of relative luminous flux, having an almost negligible impact in the quantities we wanted to measure.

The PTB research goniometer ARGon[3] (shown in Figure 19, right) has been equipped with a photometric camera LMK 5 color (TechnoTeam). With this system, high spatial resolution measurements are possible in nearly any in- and out-of-plane geometry. The camera device is a combined imaging luminance and imaging colour measurement system with an implemented CCD–sensor, which has 1364 x 1030 Pixels. In the actual measurement line this leads to a field of view of 1.15° x 1.55°, corresponding to a detection area of 28 mm x 38 mm on the sample. The spatial resolution given by the pixel size is about 28 µm x 28 µm. Effect pigment samples showing the sparkle effect can be characterized by the implemented system with respect to reflected intensity (Luminance) and, if desired, with respect to colour according to the CIE 2° standard observer.

These two measurement lines for sparkle and graininess will allow the measurement methodology to be improved to provide traceability to NMIs in the near future.

3.10.2 Proposal of an image based measurements procedure for the measurement of sparkle

From the measurements provided by the facilities presented above, and from samples collected in xDReflect (see description in subsection 0), a methodology for measuring sparkle has been developed and proposed. Adequate measurands were well-defined, as contrast of a sparkle, ensemble contrast or sparkle density. The methodology was tested by measuring three specimens with different levels of visual sparkle.

A procedure to measure well-defined and traceable quantities to characterize sparkle has been described. Experimental results have been shown at well-distributed illumination/viewing geometries within the incident plane, by using the GEFE goniospectrophotometer developed at CSIC. Sparkle measurands have carefully been defined to be independent of instrumental parameters. It has been proved that the accuracy of this methodology allows systematic variation of sparkle quantities to be characterized as a function of one of the geometric flake-based parameters. Four descriptors have been derived which may be correlated with visual attributes of sparkle, two of them describing geometrical dependence. Finally, a procedure to estimate the perceived sparkle at any given surround luminance from the measured sparkle quantities has been explained.

The proposed methodology, after tested with more measures, will be used in the new measurement lines at NMIs to measure sparkle, and to provide traceability to future equipment. Based on this activity, a new CIE Technical Committee for the measurement of sparkle and graininess will be proposed to provide to industrials a traceable, open access and performant measurement of sparkle.

This work has been published [6].

3.10.3 New colour representation and interpolation from BRDF measurements allowing to visualize the colour travel of goniochromatic samples on a screen

The colour of special effect coatings has a strong dependence on the irradiation and viewing angles, which makes their appearance very appealing. As a consequence, these coatings have become very popular in the automotive industry and in other markets, such as cosmetics or in applications as security inks. Special effect coatings consist of a transparent substrate having embedded traditional color pigments, which absorb part of the light, and flake-shaped interference pigments. They have a selective reflection due to their layered structure which gives rise to interferences, the main origin of the special effect in the coatings. This is the most important difference with respect to the effect coatings, which have metallic flakes that specularly reflect the light. The perceived difference between effect coatings and special effect coatings is the much stronger variation of hue of the latter with respect to the former. The increasing popularity of special effect coatings demands the development of new techniques and instruments to characterize their colour. Of particular relevance is to determine a reduced set of measurement geometries to completely characterize these coatings. Concepts introduced by Cramer and co-workers have contributed to the understanding of the colour shift of effect and special effect coatings on a*,b*-diagrams. An interference line is defined as the locus of calculated colour coordinates from measurement geometries with a fixed aspecular angle (the angular distance with respect to the specular direction), and an aspecular line as the locus of calculated colour coordinates from measurement geometries with a fixed irradiation angle. According to the experience of the authors, interference lines with low aspecular angles characterize the special effect pigments (the strong color shift), whereas aspecular lines may characterize the scattering by absorption pigments.

The motivation of this work was to find a clear and simple flake-based representation of the colour gamut of these coatings aligned with the previous concepts developed so far. For practical reasons, we consider it very important that the flake-based representation was easily connected to the conventional instrumental measurement geometries. This representation of the colour gamut is presented in detail and it is demonstrated for real special effect coatings.

A new representation of the colour gamut for special effect coatings has been proposed. The most important characteristic of the proposed representation is that it allows for a straightforward understanding of the colour shift in these coatings to be done both in terms of conventional irradiation and viewing angles and in terms of flake-based parameters. This representation allows the colour shift of special effect coatings to be figured out which is a very interesting alternative to the usage of goniovision devices to perceive the colour gamut. We have previously proven that the bistatic angle is almost proportional to the incidence angle on the flakes. Therefore, a different line was proposed to assess the colour shift of special effect coating on a*,b*-diagrams: the absorption line. Similar to interference and aspecular lines (constant aspecular and irradiation angles, respectively), an absorption line is the locus of calculated colour coordinates from measurement geometries with a fixed bistatic angle. It gives insight into the relative contributions of the absorption and interference pigments at different geometries in a more direct way than the aspecular lines. The proposed representation of the colour gamut was realized for six different special effect coatings: three from Merck and three from BASF Coatings. These representations visually show the colour for a meaningful number of geometries and could be used, either in an extended or a simplified way, as a basis for colour cataloging these kinds of coatings, visualized in colorimetrically calibrated displays or printing devices. On the other hand, a*,b*-diagrams allow a more quantitative analysis to be done. The representations of hue angle and chroma along the length of the proposed absorption lines show the convenience of using these lines to understand the relative contributions of the scattering at the absorption and interference pigments to the spectral BRDF at different geometries. Descriptors were proposed in these terms which may help in the quality control and design of new colour recipes for these special effect coatings. It should be noted that although absorption and interference lines allow the variation of perceptual attributes to be very clearly assessed, θinc or θflake are almost constant along the length of these lines and therefore measurements restricted only to one of them would provide some spectral or angular redundant information. For this reason, when the question is to select a reduced number of nonredundant measurement geometries to completely characterize special effect coatings, to lie only on these lines is not adequate. For example, in a previous work we proposed a set of nine measurement geometries organized in two aspecular lines with θ_i= 20° and 50° which provide nonredundant information about variations of chroma, hue, and lightness and allow spectral reflectance at any other geometries to be estimated using a PCA-based procedure. This kind of organization in aspecular lines is also common in commercial portable instruments.

The complexity of the color of special effect coatings can be considerably simplifies by using the ideas suggested in this work. The very simple way of representing the samples can be easily implemented in BRDF databases, allowing its visualization. This work has been published [1].

3.10.4 Inter-instrument agreement of specular glossmeters evaluation

In order to numerically quantify and to ensure consistency of the visual appearance of the end product, many industries perform colour and gloss measurements, for the results of which they define maximum tolerances during quality control. For this, they may primordially rely on precision data for repeatability and reproducibility as reported by instrument manufacturers, who develop their instruments according to standardized measurement geometries defined in international standards. Yet, apart from some older studies, little has been reported about the agreement between gloss measurement results obtained with gloss meters from different instrument manufacturers over an extended glossiness range.

An investigation of the inter-instrument agreement between specular glossmeters which conform to universally adopted gloss standards has been performed. Six commercially available instruments, manufactured by three different companies, and twenty five gloss artefacts, with specular gloss values ranging between 2 and 110 gloss units (60° geometry), were selected for use in the study. The repeatability and reproducibility of the instruments was assessed according to the criteria described in ASTM D523-14 and ISO 2813:2014, and to the specifications reported by the instrument manufacturers. Ray tracing simulations were performed by use of the BRDF measurement data of two samples, and based on the standardized optical design of the specular glossmeter, in order to get a better insight on the expected tolerances of the gloss readings from a theoretical point of view.

On average the practical results indicate that both the repeatability and reproducibility values are higher than those specified in the recommendations and by manufacturers. Ray tracing simulations confirm this finding. While specified repeatability and reproducibility thresholds are based on ideal standards, in practice there are parameters that can lead to significant higher deviations.

From this work, we can conclude that care should be taken when analyzing measurement results obtained from different instruments, and when defining tolerances for evaluation of gloss measurements. Gloss measurements using commercial glossmeters may engender measurement uncertainties far beyond 1 GU, the value typically stated by manufacturers. More information on how the repeatability and reproducibility of commercial gloss meters is being determined should therefore be made public, while repeatability and reproducibility values should be stated for each measurement geometry and gloss range. In this respect, further ray tracing simulations using a variety of BRDF distributions in the different gloss measurement geometries could provide useful information.

This work has been published in the Journal of Coatings and technology [16].

3.10.5 Identification of non-negligible polarization dependence of the radiance on reflectance standard artefacts

Due to the relative insensitivity of the human eye to polarization, appearance quantities should be measured with unpolarized incident and scattered light. However, most goniospectrophotometers suffer from polarizing elements in the optical systems, particularly diffracting elements where spectral measurements are being made. Therefore, the measurement process involves making measurements in each of at least two polarization states and averaging the results. The intercomparison of goniospectrophotometers carried out during this project (see objective 2) brought to light the potential magnitude of errors if this is neglected and stimulated an effort to model the effect.

MSL made measurements of the ratio of the BRDF for s-polarized incident light and unpolarized detection with p-polarized light and unpolarized detection for the two comparison geometries 0°:45° and 45°:0°. These results showed a simple relationship between the ratio and the average BRDF which was independent of wavelength, or sample over the set of six matte ceramics measured

Since the xDReflect project, a significant amount of effort has been undertaken between MSL and PTB (where similar measurements have been carried out as well as at a range of other geometries) to build a microfacet model to describe the measurements.

The measured ratios described above are plotted in Figure 20, where the different coloured symbols represent different ceramic samples

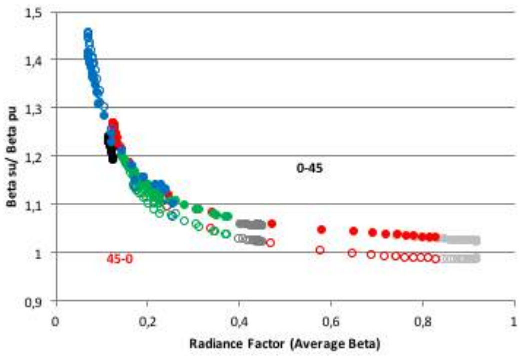

Figure 20 : Measured ratios of the BRDF for s-polarized incident light and unpolarized detection with p-polarized light and unpolarized detection for the two comparison geometries 0°:45° and 45°:0°. Different coloured symbols represent different ceramic samples

As can be seen, the ratio can be very large for dark samples in particular so the effect of polarization cannot be neglected even for matte samples. In addition the apparently simple relationship suggests a simple model to describe the relationship and has stimulated further effort in this regard.

Understanding the effect of polarization on bidirectional measurements is vital to estimating and controlling errors in BRDF measurements. In turn, well-constructed uncertainty estimates build confidence in measurement and make traceability in this field possible. In addition a reliable model for the effects of polarization may mean that only one polarization must be measured directly, potentially saving time and effort. The results of this work were presented by poster and oral presentation at NewRad 2017 in Tokyo. (OPM-O-1 Polarization dependence of bidirectional reflectance from ceramic tiles, Annette Koo, Oral presentation at NewRad 2017, Tokyo, OPM-PA-4 Polarization properties of white, grey and coloured matte diffuse reflection standards, Tatjana Quast, Poster presentation at NewRad 2017, Tokyo).

3.10.6 Proposal of method for UV adjustment to improve adjustment of UV contents of D50 illuminant

The quality of UV content adjustment calibration of commercial measurement devices commonly used in printing industries are made according to ISO standards (ISO2470-1, ISO 11475, and ISO 11476) for the standard illuminants, C and CIE D65, respectively. The method proposed by ISO is simple. It is based on one single assigned value. Because of the simplicity, these methods have gained great popularity in papermaking industry. Yet, there has been little evidence indicating how accurate the total spectral radiance factor corresponding to the single assigned value is reproduced and the single point method can lead to metamerism issues.

A new method for UV adjustment has been proposed to improve adjustment of UV contents of the standard illuminant D50 the standard illumination used in printing industry. Instead of a single assigned value, a full spectrum is assigned to the reference standard. Comparisons have been done with the ISO method. We found that the major differences occur in the blue band where fluorescence is strong. At a few wavelengths, the differences may be up to 4–5%. Nevertheless, their colour differences corresponding to the assigned spectra and those obtained from the UV adjustments are still smaller than unity (1 DE*) for all of the illumination conditions.

The work has been summarized in an article presented at SPIE conference in San Diego, August, 2014. Two fluorescent reflectance standards for the standard illumination D50 have been developed. This work will contribute to a better control of illumination sources in color of measurement. This will in turn lead to higher quality of printed color reproduction.

3.10.7 *Measurement method proposal based on commercial flatbed colour scanners to characterize grating-based holographic paper.*

A holographic paper consists of cells of reflective diffraction gratings, of which the perceived color changes with illumination/viewing geometries. For a given pair of illumination/viewing angles, the perceived colour varies even with the orientation of the measured sample. Amid to these complexities there is no appropriate measurement method available to characterize such papers which is a problem for the quality control. The appropriate way to do it would be the measurement of the BRDF for a given set of angular configurations, but these measurements are too expensive, too fragile and too long at the moment, to be implemented on a paper production unit.

We proposed a new measurement method that is applicable to holographic paper or film, using a commercial flatbed scanner. Mathematical expressions for the proposed method, which govern the diffraction behavior of holographic patterns under a 2D-illumanation source and in accordance with the “rotate-scan” measurement concept, have been deducted. By adapting the “scan-rotate” measurement strategy, the basics of the holographic paper (or film) of numerous holographic patterns and in any size, can be obtained simultaneously, i.e. the grating periodicity and the orientation within a grating cell, the shape and spatial distribution of the grating cells, and defects of the holographic patterns amid to surface roughness (topographic variation) of the base paper and inhomogeneity of the metallic coating.

The work has been presented at TAPPI Conf, Oct. 2016. Considering the novelty and potential usefulness, we wrote a full article which will be published in the near future.

Industrial areas that benefit from this work are paper and printing industries.

3.10.8 Conclusion

Two new measurement lines were set up for the measurement of sparkle and graininess and an image based measurements procedure for the measurement of sparkle was developed. This was essential for the automotive industry, where more than 80% of their global production uses sparkle effect, but no clear measurement proposal to control the quality of the product previously existed.

Based on the work on measurement time (see Objective 5), a set of 10 optimal geometries for colorimetric measurement of iridescence samples based on interferometric pigments were produced. The uptake of this result by spectrophotometers manufacturers has the potential to launch a new generation of multi-angle spectrophotometers that would be more efficient than the existing ones. To visualise the colour for these samples on a screen, a new colour representation and interpolation from BRDF measurements was developed to support industry in monitoring the quality control of the appearance of coatings. Comparisons of specular glossmeters by the project, demonstrated weakness in the glossmeter’s geometries and specifications.

3.11 Objective 11: Propose a new standard and recommendations for gloss measurements that take into account the visual perception, the background and is adapted to modern surfaces

Gloss is a visual attribute. It plays an important part in the perception of the total appearance of a material. It is implicated in the material identification, in the evaluation of the polishing level of the surface and is linked with the sensation of quality. Gloss also participates in our understanding of the environment and its coherence. It allows us to deduce geometrical cues regarding our surroundings like the position and orientation of a light source, the curvature and orientation of an object.

When an observer is asked to evaluate the gloss of a sample, s/he looks in the specular direction and rotates lightly the sample, as if trying to access not only the size but also the shape of the specular peak.

To understand the reason behind this, we set up an experiment where we used six different samples and confronted these over two measurement types: High angular resolution BRDF with the goniospectrophotometer ConDOR and microtopography through Coherence Scattering Interferometry (CSI).

We could conclude that the visual system extracts much more information than gloss when scanning the specular peak.

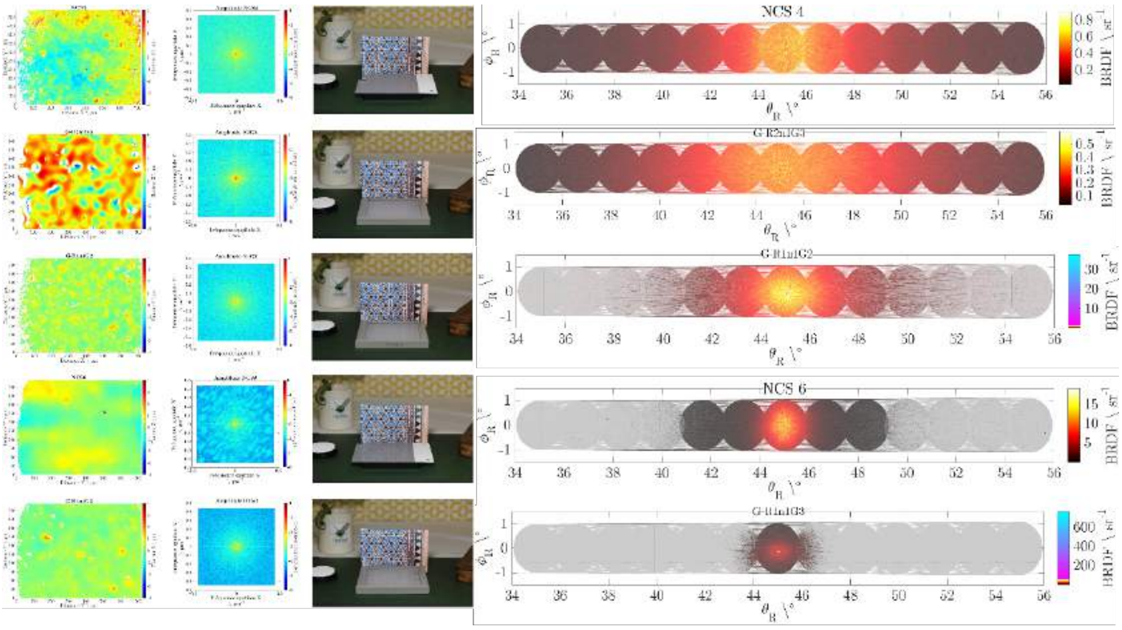

Figure 21 Measurements carried on the five selected samples: Microtopographies and their bidimensional FFT, photogrpahs of the samples and BRDF measurments on ConDOR

The results are summarized in Figure 21. The first column corresponds to microtopography of the surfaces, the second column corresponds to the bidimensional Foureir Transform of the microtopography. The third column exhibits a photograph of the sample and the last one, the BRDF measurement in the plane of incidence with an illumination incidence of 45°. Samples are ordinated according to increasing gloss index by row.

Our results show a link between bi-dimensional FFT of surface roughnesses and BRDF measurements. Each FFT plot can be associated without mistake with its corresponding BRDF measurement. This link has now to be studied, in order to describe a strong link between the two quantities. This work opens a new approach between BRDF and roughness measurements

Based on psychophysical experiments made on gloss scales with different lightings and environments, recommendations were produced for the right way to evaluate visual gloss. However, due to the high complexity of the specular peak BRDF, which was not known before the project, it was not possible to find a correlation strong enough between the visual result and the optical results to develop new standard measurements. Further investigations are planned in the follow-on EMPIR project 16NRM08.

3.12 Objective 12: Propose new types of reference artefacts for calibration and characterisation of goniochromatism, gloss and fluorescence

3.12.1 Discovery of spectral changes in the angular profiles of reflectance for fluorescent material

Fluorescent brightening agents are widely used in various industries to enhance the appearance of materials. The angular profiles of emission and reflectance of fluorescent surfaces have been shown to deviate from Lambertian behaviour, however, in industry and calibration facilities single geometry measurements are often used, which requires assumptions to be made on the angular distributions. In addition, the angular distribution of reflectance has been shown to deviate from that of fluorescence. It has been shown that the angular distribution of reflectance is dependent on the excitation wavelength in some materials e.g. paper. The question, whether this is true for PTFE and ceramic materials was still to be answered. These angular and spectral effects may cause measurement errors when single geometry bidirectional measurements are carried out. The angular distributions can be taken into account by using goniometrical measurements, which however, result in increased calibration time and cost. Alternatively, a reference material could be used where the angular dependencies are minimised.

Several PTFE based and ceramic diffuse reflectance luminescent standard materials were measured for angular profiles of reflected radiance factors. In addition, qualitative and quantitative modelling was performed on the materials.

The spectral variations of the angular profiles of reflectance from these materials was found to depend heavily on the absorbance of the luminophore. The effects were larger for PTFE based materials (up to 22% variations in profiles) than for the ceramic panel (up to 11%). The effects were small when the reflectance of the material was large (>0.6), i.e. absorbance was small. The effects were minimised in CIE recommended measurement geometries. The detailed results are published [17].

The new knowledge on the spectral dependence of angular reflectance profiles can be useful for reducing measurement uncertainties when the reference sample and the sample under measurement contain different types and concentrations of fluorophores, are measured at different geometries or when measurements are performed with different UV contents of the irradiation spectra.

3.12.2 Production of a new type of reference material for fluorescence measurements in collaboration with Lucideon

Fluorescence is a process in which light is absorbed by a molecule and re-emitted at longer wavelengths. Various scientific and industrial applications make use of fluorescent brightening agents to enhance the appearance of materials (e.g. textiles, paper and plastics). For accurate characterisation and reproduction of appearance, relative and absolute measurements of fluorescence characteristics are needed. The angular emission and reflectance of fluorescent surfaces have earlier been shown to deviate from Lambertian behaviour, however in industry and calibration facilities single geometry measurements are often used, which requires assumptions to be made on the angular distributions. In addition, the measurement geometry of the calibration of the reference sample is often different from that of the routine measurements. The angular distributions can be taken into account by using goniometrical measurements, which however, result in increased calibration time and cost. Alternatively, a reference material could be used where the angular dependencies are minimised.

A sample was made by Lucideon, where the luminophore was confined in a thin layer on the surface of the sample. The sample was measured for luminescence and reflectance to find out whether confinement of luminophore will result in more Lambertian angular reflectance and fluorescence emission profiles than when the fluorophore is in the bulk of a translucent material as in the conventional commercially available polytetrafluoroethylen (PTFE) based samples.

The measurement results indicate that the novel sample has more Lambertian reflectance and emission angular profiles than the conventional samples. The deviations of the reflectance and emission profiles were up to 13% from Lambertian for the novel sample and up to 35% for the PTFE based samples. The results are in form of a dataset and have been published [17]. In addition, the material minimises the spectral variations of angular emission profiles. This point is also described in this article.

The novel sample can be useful for improved uncertainties for single geometry measurements in industry where 45°/0° and 0°/45° geometries are not available e.g. commercial instruments with fixed angle of 90° between the irradiation and viewing angles.

3.12.3 Production of a novel gloss scale made of 40 glass samples in collaboration with St Gobain

Gloss has often been described using the notion of a reflected flux measured in various angular configurations. However, over the last decade, studies have been unveiling a more complex description of this phenomenon.

First, the gloss constancy property has implied that whatever the angular configuration in illumination and observation, gloss was intrinsic to a given artefact. Secondly, the visual system does not rely on the amount of flux reflected by the sample. This was addressed by studies over the effect of additional diffuse illumination during gloss perception experiments. Finally, the question of gloss dimension has been asked on several papers, either based on virtual or real artefacts. The data related to gloss should then be embedded within and around the specular peak. We note that present increase in number of multi-angle instruments, both commercial and scientific, is strongly interwoven with such considerations from the industrial point of view. In order to describe gloss in a way consistent with its visual perception, a morphologic characterization of the specular peak is needed. From this point, one should notice the lack for gloss scales toggling with the various topologic properties of the specular peak.

We consequently need to design samples through methods affecting the specular peak. One of the possible way to do so is to use sol-gel chemistry. The substrate of our samples is Saint-Gobain Satinovo® diamond glass depolished on the back side. On the depolished back of the sample, we deposit a mineral paint, we thus avoid multiple reflection between the glass interfaces. On the front of the sample is deposited hybrid silica layer. It is then patterned by nanoimprint.

42 samples were developed accordingly. We built these according to three distinct surface topologies: a replica of three samples from a NCS reference gloss scale, a scale based on the thermal relaxation of a nanoimprinted polymer and an untextured scale for high gloss levels. The samples were decline in three hues (black, grey and white) and two refractive indices. All this work has been carried out at St Gobain research Center in Aubervilliers (France). St Gobain, as stakeholders of the project, opened the access to its facilities for free to xDReflect.

Figure 22 the xDReflect gloss scale is made of 42 samples.

The multivariate scale developed during xDReflect is an important tool to understand the links between hue, surface topology, surface refractive index, BRDF and gloss. It is now used on multi-instrument comparisons to study the link between roughness and BRDF. This work has been presented on a poster during NewRad 2014 (G. Ged, J. Teisseire, E. Garre , M.E. Himbert G. Obein, “Development of a controlled metrological gloss scale,” Newrad 2014., Espoo, June 2014).

3.12.4 Characterisation of the roughness of a gloss scale using five complementary methods

Gloss, as optical quantity, is known to strongly correlate with the roughness of a surface, but how details in the surface topography influence the perceived gloss is less well known. Also, depending on the type of material, the size and shape of the surface roughness and other factors, different evaluation techniques need to be used in order to capture the significant surface features and not introduce measurement errors. The aim of this work was to contribute to the knowledge about the relationship between gloss and surface topography as well as providing information about the suitability of different measurement techniques for evaluating certain materials and surface structures.

Six samples with different refractive indices, different gloss levels and different roughness types have been examined using five different techniques: AFM, CSI, CM and mechanical profilometer (at RISE) and optical roughmeter based on angle-resolved scattering theory (at CNAM). The evaluated samples were manufactured using novel techniques based on sol-gel chemistry for accurate replication of surface structures in combination with controlled thermal relaxation processes (see previous section).

The surfaces of the six selected samples were thoroughly investigated using the measuring techniques described above, with the aim to verify the outcome of the novel manufacturing processes in terms of distinct levels as well as types of surface roughness. The evaluation captured surface structures in different wavelength intervals utilizing different measurement methods. Also, PSD functions calculated from the measurements was used to determine suitability of techniques for different roughness scales. Measurements show the expected surface characteristics as well as different rms roughness values intimately connected to the perceived glossiness, and that the selected samples had very specific and different surface characteristics originating from their manufacturing processes. Some additional results and conclusions were:

- The usage of PSD analysis is a strong tool for identification of the differences and equalities between instruments measuring similar topographies enabling a selection of the proper instruments for measuring at given frequencies or combination of frequencies.
- The analysis based on PSD and motif analysis reveals the surface topography frequency content as well as the number, height and area of significant features.
- The overall gloss levels of the samples were in agreement with the manufacturing tolerances although differences where identified between sample pairs with the same nominal gloss level depending on the variation in spatial frequency content.
- The roughnesses of the studied samples were shown to closely correlate to the gloss levels due to specifics in the manufacturing process.

The results show that the novel manufacturing techniques developed within the project have the potential to be used for customizing a gloss scale with distinct gloss levels and with significantly different surface characteristics. Also, the measurement results and the proposed methods of evaluation provide important knowledge when choosing instrumentation and parameters for proper characterization of various types of surfaces. This work has been published [8].

3.12.5 Development of artefacts for sparkle and colour assessment in collaboration with Merck and Azko Nobel

To evaluate visual attributes of materials through subjective responses, providing a connection between the visual appearance, evaluation and metrological characterization of a material is necessary since the visual appearance of a product is the most important criteria used by consumers when deciding what to buy. Therefore, it is necessary to choose artefacts, different in their visual attributes that have metrological characteristics that are very well defined in order to perform subjective tests on the perception of visual attributes.

UA collected around 500 samples from different automotive and coatings companies in order to have a large collection to select the appropriate colour samples for each visual experiment. The colour measurements were carried out with a BYK-mac multi-angle spectrophotometer, assuming D65 illuminant and CIE 1964 standard colorimetric observer. This instrument provides colour measurements considering a light source placed 45° with respect to the perpendicular to the sample, and detection at six different angles: 45°x:-60°, 45°x:-30°, 45°x:-20°, 45°x:0°, 45°x:30° and 45°x:65°, respectively.

Figure 23 Different set of color samples from different automotive suppliers.

These colour samples were divided by considering different characteristics:

- achromatic and chromatic colors: to test all the terms of colour difference formula for gonioapparent materials (ΔL, ΔC, ΔH)
- colour samples with low, medium and high flop: to test the flop terms of colour difference formula for gonioapparent materials.
- colour samples with different texture values (sparkle and graininess) to analyse the influence of the colour background on the visual detection of texture and to test the prediction model for sparkle and graininess according to the colour of the sample and the particle size.

Figure 24 Samples with silverdollar pigment (left) and with cornflake pigments (right)

Finally, three different sets of samples with different pigments were defined:

- Set 1: Iriodin 9103, Iriodin 9119, Stapa Hydrolan 8154, Stapa Hydrolan 2154, Cornflake, Xirallic T60-10 SW, Xirallic T61-10 WNT, Silverdollar, with different PMC and pigmentation in a waterbone/basecoat binder system.
- Set 2: Chromaflair Magenta, Iriodin 9221, Iriodin 9225, Colorstream T20-01 WNT Viola Fantasy and Colorstream T20-04 WNT Lapis Sunlight with different PMC and pigmentation in a waterbone/basecoat binder system.
- Set 3: Eckart pigments (metalure, Stapa Metallux, Stapa Metallic Cornflake) with pigment size.

The three sets of artefacts presented here have representative characteristics in terms of colour, colour flop and surface texture. They have been specially selected in close cooperation with the pigment manufacturers to serve as reference sets. Reflectance measurements have been carried out in different geometries and for a large spectral range. The acquired BRDF data are made publicly available in the BRDF database on the xDReflect project webpage (http://www.xdreflect.eu/brdf-data/) and can serve as exemplary reference data. Work based on these measurements have been published [7].

3.12.6 Conclusion

A set of 18 ceramic samples were developed for inter-laboratory comparisons on the reflectance factor.

A new type of reference material for fluorescence measurements was produced which shows better Lambertian angular fluorescence emission profile (used for matt surfaces) than currently commercially available materials. A spectral change in the angular profiles of reflectance for fluorescent material was also discovered. This spectral change may impact the quality control of pulp and paper or textile industries, where fluorescent dyes are used.

A novel gloss scale made of 40 samples was constructed. The roughness, the BRDF and the specular gloss of these samples were characterised. From these measurements, the high complexity of the BRDF in and around the specular direction was demonstrated for the first time, and a link with the roughness has been identified.

Artefacts for sparkle and colour assessment have been designed and selected for two different campaigns, in collaboration with Merck (a global healthcare company) and Azko Nobel (a leading global paints and coatings company and major producer of specialty chemicals), industrial stakeholders. Based on the measurement of 66 samples, 9 were identified as representative of full range of effect pigments for visible iridescence effects and are now available for industry to use.

3.13 Conclusions

Improvement of primary goniospectrophotometers in order to progress in BRDF measurements and reduce the measurement uncertainty

Progress was made by each partner on its goniospectrophotometer system. There is now an increased capacity of BRDF measurement in Europe with different facilities having slightly different capabilities; i.e. one increased the angular resolution, one the spectral range and the third the dynamic range. A common understanding has been developed to allow the comparisons that were carried during the project to guarantee the control of the quantity. European NMIs are now ready to face the current needs of industries in the field of BRDF measurement, and are also ready to face future innovation on visual or functional effects on materials.

Development of models for data compression, data representation and data handling for BRDF measurement

As BRDF is a 6 dimensional quantity (2 angles to describe the direction of illumination, 2 angles to define the direction of observation, 1 wavelength and 1 polarisation), the elaboration of the strategy for its measurement is, by itself, a challenge. It is also difficult to archive, exchange and exploit measurements. The results obtained in this project made significant progress in the way to sample, control, plot and share BRDF measurements. The recommendations must now be consolidated and promoted to instrument manufacturers, the computer graphics community and industrial end users, using support from a standardisation body such as the CIE.

Understanding of correlation between the visual appearance and the BRDF

Within the project we focused on the two visual attributes that currently have a high impact in industry and are not well measured: i.e. gloss and sparkle. Clear indicators have been identified in sparkle that generate the visual sensation and open the route for its measurement. This topic is now ready to be investigated at an instrumental level as part of EMPIR project 16NRM08 BiRD. The effect of the shape and size of the light source on gloss sensation were understood in the current project and the first step toward the creation of a ‘gloss standard observer’ has been made.

Developing standard procedures and transfer artefacts

A method for the measurement of sparkle, and a protocol to characterise iridescence samples were developed. The project also built a new generation of standard artefacts for sparkle, gloss and fluorescence effects that will form the basis of the traceability and dissemination of the reflectance based quantities in the future. All these samples are now available for industrialists and researchers to carry out further investigations on BRDF measurements and models, to test measurement equipment or to work on visual perception.

4 Actual and potential impact

This project validated reliable optical measurements, with traceability to the SI, to describe the overall appearance of modern surfaces. It developed new efficient measurement strategies and new standard artefacts that will enable industries to characterise and control the visual appearance of the surfaces they produce.

Dissemination activities and stakeholder engagement

22 papers were published by the project in relevant journals, including Applied Optics, the Journal of the Optical Society of America, Optics Express, Metrologia, and Colour Research and Application.

46 papers were presented at conferences, including leading conferences in the field such as the Colour & Imaging conference, CIE Expert Symposium and NewRAD. 7 training courses and workshops on such topics as the 'Goniometric characterisation of sources and materials' and the 'Fundamentals of colorimetry' were also held which were attended by around 200 people.

By the end of the project, its website http://www.xdreflect.eu had received over 59 000 visits.

4th CIE Expert Symposium on Colour and Visual Appearance (6-7 Sept 2016, Prague, Czech Republic):

To close the project, in September 2016, CMI, with the scientific support of the xDReflect consortium, organized the 4th CIE symposium on visual appearance in Prague. 162 persons attended the event coming from 27 different countries. This major event in the field of visual appearance has been initiated by xDReflect research and shows the major influence of the JRP at a global level. CMI, with the scientific support of the xDReflect consortium, organized the 4th CIE symposium on visual appearance in Prague. This event has been a joint conference between CIE Div1 (Vision), Div2 (Measurement of light) and Div8 (Image Technology). 81 abstracts coming from 24 countries have been received. 162 persons attended the conference coming from 27 different countries. 14 industrial stakeholders of xDReflect where present. CNAM chairs the International Scientific Committee (ISC) and CMI, KULeuven and CSIC are members of the ISC. This major event in the field of visual appearance has been initiated by xDReflect research and shows the major influence of the xDReflect consortium at a global level.

More details here: http://div2.cie.co.at/?i_ca_id=985

Figure 25 *Attendees of the 4th CIE Expert Symposium on Colour and Visual Appearance*

CIE Tutorial on BRDF measurements, (5 Sept 2016, Prague, Czech Republic).

Before the symposium, a one day tutorial has been given by xDReflect on Visual Appearance Fundamentals and Measurement. The guidelines on standard test method for visual evaluation of goniochriomatic samples, on lighting arrangements to improve visual experience in exposition, on viewing cabinets for sparkle evaluation, on the influence of the pigment particle size on sparkle and on recommendation for visual assessment of gloss have been presented to the 89 attendees of the tutorial. The tutorial was in 6 sections:

1. Introduction - Visual perception of materials (P. Hanselaer), 30mn
2. Fundamentals in radiometry, colorimetry (T. Goodman), 30mn
3. Fundamentals of BRDF (A. Koo), 30mn
4. Gloss (F. Leloup, G. Obein), 75mn
5. Goniochromatism (C. Strothkaemper, A. Koo, F. Verdu), 75mn
6. Sparkle and graininess (P. Iacomussi, A. Ferrero, F.Verdu), 75mn

Figure 26 The CIE tutorial in Prague mixed formal teachings, debates and experiences with samples (More pictures from the Tutorial and Symposium are available on the webpage www.xdreflect.eu)

Dissemination and exploitation of project outcomes according to the exploitation plan

Best practice guideline	PTB	Best practice guide for color measurements and color coordinates uncertainty evaluation made publicly available on JRP website	Users of color measuring instruments
Comparative measurements	Consortium	Improve the uncertainty budgets for BRDF measurements based on the scale comparison	Customers that want BRDF calibrations
Model	PTB	Model for the understanding of effect pigmented coatings	People involved in the manufacturing, application or measurement of effect pigmented coatings
Best practice guideline	INRIM, REG2(UA)	Best practice guides and guidelines for lighting source influences on appearance	Consortium, community Lighting designers Lighting booth manufacturers
Best practice guideline	INRIM, REG2(UA)	Further R&D on radiometric characteristic of sparkle	Instrument manufacturers
Psychophysical measurement techniques and analysis	REG2 (UA)	New artefacts for goniochromatism and visual textures	Special-effect pigment manufacturers, instrument manufacturers, car makers and its coatings / plastics providers
Model / Patent	CSIC, REG2(UA)	Model for the understanding and the color palette of any gonio-apparent specimen	People involved in the manufacturing or measurement of special-effect pigments
Statistical model and analysis	REG2 (UA)	Proposal of the minimum number of measurements of multi-angle color, sparkle and graininess using the same instrument	Instrument manufacturers Consortium
Psychophysical and statistical procedures	REG2 (UA)	Design of visual experiments and statistical analysis for improving structural, instrumental and visual correlation in color and visual texture	Special-effect pigment manufacturers, instrument manufacturers, car makers and its coatings / plastics providers Consortium
New professional curriculum profile	REG2 (UA)	MSc course in Color Technology for the Automotive Sector, including internships linked to the MSc Thesis project	Special-effect pigment manufacturers, instrument manufacturers, car makers and its coatings / plastics providers Other color industries (cosmetics, plastics, printing, etc.)

Contribution to standards

15 presentations were given to regulatory bodies, including the BIPM Meeting of representatives of State Parties to the Metre Convention and of Directors of National Metrology Institutes, EURAMET Technical Committee for Photometry and Radiometry (TC-PR), DIN NA 025 on colorimetry, CIE Div2 annual meeting, ASTM E12 on colour and appearance, ISO TC 06 on Paper, board and pulp and the BIPM Consultative Committee for Photometry and Radiometry (CCPR).

The following 7 good practice guides and guideline documents were produced and have been published on the project website:

1. Guidelines for standard test method for visual evaluation of goniochromatic samples
2. Guidelines for lighting arrangements to improve visual experience in exposition
3. Guidelines for viewing cabinets for sparkle and graininess sample evaluation
4. Guidelines on the influence of the pigment particle size on the comparison of sparkle and graininess
5. Guidelines for new standard test method for visual evaluation of gloss
6. Good practice guide for fluorescence measurements of solid surfaces by the two-monochromator method
7. Good practice guide for colour measurements

Early impact

Within IND52 xDReflect, considerable progress has been made by NMIs to improve or develop absolute goniospectrophotometers, enabling the measurement of the full BRDF (in full space rather than just specific directions) at the highest metrological level. Eight of these instruments have been validated by a comparison on grey and colour ceramic tiles. As a result NMIs can now realise the BRDF scale at a satisfactory level of agreement, constancy and typical 5 % uncertainty and are able to provide this in almost any geometry to the customer. Primary metrological labs are now in a position where they can formulate a proposal to normalise BRDF measurements of particular materials, and to provide guidance on how to sample the BRDF space efficiently and to process and visualise the measurement data in a convenient way.

Examples of the project's outputs being taken up by the relevant communities include:

- St Gobain Research (a leading producer of building materials and glass) has used the high angular resolution BRDF measurement set up by CNAM to characterise its new functional surfaces.
- A presentation of the measurement strategy and global colour estimation extrapolation for goniochromatic samples was given to coatings scientists at the companies Merck and BASF (the largest chemical producer in the world).
- Most of the project’s work on sparkle, including the detection distance, a method for the estimation of iridescence colours outside Rösch-MacAdam colour solids, and an interpretation of imaged based BRDF capture, has been taken up by Merck and BASF.
- The project’s procedure for the measurement of sparkle was used by one of the world leading portable spectrophotometer manufacturers to characterise samples.
- A PhD has been launched between Merck and the University of Alicante to develop new visual and instrumental correlations for sparkle based on the visual and metrological results of this project
- A PhD has been launch between Seat and the University of Alicante to develop new improvements in visual harmony management of the car body based on the visual and instrumental results of the project.
- The colour difference methodologies produced by the project were tested at Toyota Motor Europe
- The project’s method for testing the colour difference on iridescence samples has been tested by the University of Granada, the University of Alicante and AUDI.

- Partially driven by the project's results, CIE has launch the technical committee TC2-85 on *"Recommendation on the geometrical parameters for the measurement of the BRDF"* .

Potential impact

The results from this project are expected to have impact on European industries through:

- Accurate and stable BRDF measurements, traceable to NMI reference standards, leading to improvements in quality control during the production process (gloss uniformity, iridescence reproduction).
- Providing objective and scientific means of checking that specifications agreed at the contract level have been met rather than using subjective expert judgements, and therefore improving client-supplier relations and ability to deliver.
- Reducing the costs in production due to a better knowledge of the border between "the things that are seen" and "the things that are not seen", allowing the manufacturer to know more accurately its production tolerances.
- Encouraging industry to develop new measurement devices in the field of reflectometry and visual effect characterisation, for example iridescence, gloss, fluorescence, sparkle and graininess.
- Fluorescent agents are used extensively by textile and paper industries and better control of the measurement, and thus less error, will make them use less fluorescent agent, save money and reduce pollution.

5 Website address and contact details

The xDReflect website (http://www.xdreflect.eu/) has been launch few days after the first kick-off meeting. At the end of the project time, the website had received 59 253 visits.

Figure 27 : The webpage of the project, with restricted member area and collaborators area

A dedicated access to the JRP website has been opened to the collaborators in order that they can have access to the materials presented during the meetings. 45 persons registered to have access to the restricted area. Best practice guides and guidelines have been published on JRP website for appearance related measurands (colour, gloss, fluorescence).

6 List of publications

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The following people have expressed their interests in this work:

2C (France), AUDI AG (Germany), Axiphos (Germany), BASF Coatings GmbH (Germany), BYK-Garner GmbH (Germany), Centro de Estudios y Experimentacion de Obras Publicas (Spain), Comité Professionnel de Développement Cuir Chaussure Maroquinerie (France), Commission Internationale de l´Eclairage (Austria), Cramer Forschungsinstitut (Germany), Data Color (Germany), Deutsche farbwissenschaftliche Gesellschaft e.V. (Germany), EFS (France), Eldim (France), Escolab nv (Belgium), Fogra Forschungsgesellschaft Druck e.V. (Germany), Grupo Antolin (Spain), Konica Minolta (Germany), Konica Minolta (Japan), Lucideon (United Kingdom), Maymó Cosmetics, S.A. (Spain), Merck KgaA (Germany), Moët Hennessy – Louis Vuitton (France), Munksjö (France), NUBIOLA (Spain), Pole Optique Rhone Alpes (France), PPG IBERICA SA (Spain), Rhopoint Instruments Ltd (United Kingdom), SEAT (Spain), SKODA auto as (Czech RePublic), St Gobain Recherche (France), TechnoTeam Bildverarbeitung GmbH (Germany), Toyota Motor Europe (Japan), TQC (Netherlands), UPM goup (Finland), WITTE Nejdek Ltd (Czech RePublic), X-Rite GmbH (Germany).