"Multidimensional Reflectometry for Industry" (xD-Reflect) an European research project

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ABSTRACT

The European Metrology Research Program (EMRP) is a metrology-focused program of coordinated Research & Development (R&D) funded by the European Commission and participating countries within the European Association of National Metrology Institutes (EURAMET). It supports and ensures research collaboration between them by launching and managing different types of project calls. Within the EMRP Call 2012 "Metrology for Industry", the joint research project (JRP) entitled "Multidimensional Reflectometry for Industry" (xD-Reflect) was submitted by a consortium of 8 National Metrology Institutes (NMIs) and 2 universities and was subsequently funded. The general objective of xD-Reflect is to meet the demands from industry to describe the overall macroscopic appearance of modern surfaces by developing and improving methods for optical measurements which correlate with the visual sensation being evoked. In particular, the project deals with the "Goniochromatism", "Gloss" and "Fluorescence" properties of dedicated artifacts, which will be investigated in three main work packages (WP). Two additional transversal WP reinforce the structure: "Modelling and Data Analysis" with the objective to give an irreducible set of calibration schemes and handling methods and "Visual Perception", which will produce perception scales for the different visual attributes. Multidimensional reflectometry involves the enhancement of spectral and spatial resolution of reference gonioreflectometers for BRDF measurements using modern detectors, conoscopic optical designs, CCD cameras, line scan cameras, and modern light sources in order to describe new effects like sparkle and graininess/coarseness. More information and updated news concerning the project can be found on the xD-Reflect website http://www.xdreflect.eu/.

Keywords: Goniochromatism, Gloss, Fluorescence, Modelling and Data analysis, Visual perception, Sparkle, Graininess

1. INTRODUCTION

Objects that have identical shapes can be identified through visual surface attributes such as color, gloss, texture, transparency, graininess or sparkle. The compilation of these visual attributes gives the appearance of the surface.

The appearance of a product is quite important for diverse industries, e.g. automotive, cosmetics, paper, printing, packaging, coatings, plastics, steel industries, etc., as this is frequently one of the most critical parameters affecting customer choice. For this reason, within the last 20 years, significant effort has been made by the manufacturers to produce new and sophisticated products which evoke specific visual effects, like metallic colors, goniochromatic pigments, deep matt finishes or sparkle effects for instance [1, 2].

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As a consequence, the need for new measurement methods, setups and standards increases in order to provide relevant quantitative data, in one hand to ensure reproducibility and quality control, assuring the visual and instrumental correlation, and in the other hand to sustain the research of new visual effects from new generation of dyes and pigments and surface treatments [3].

Current standards and artifacts proposed by the NMIs to industry to ensure traceability of their measurements are limited to the visual effects they are able to generate. For instance, in color 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 (Commission Internationale de l´Eclairage, International Commission on Illumination) [4]. This is really 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 poorer for the other visual attributes like gloss where the standards have not evolved since 1978 or for fluorescence, where the measurement methods comes from non-fluorescent materials and are today inadequate for application to fluorescent materials.

There is the perception that the special-effect pigment industry and their derived sectors (such as cosmetics, automotive, etc.), progress faster than the associated metrology standards. It seems necessary for the metrology institutes to manage these scientific-technological advances in a proactive way, anticipating the next generation of special-effect pigments and visual effects (and their colored products) for the maximum set of industries.

The industry needs new measurement methods and new standard transfer artifacts that allow the characterization of the optical behavior of modern surfaces. These new methods and associated artifacts have to be able to facilitate the quantification of different novel optical effects such as sparkle (a phenomenon that is perceived as many tiny but very intense light spots, like bright stars twinkling at the night sky) or goniochromatism [5]. For these new measurement methods to be taken up by industry, they need to be easily interpretable. In addition, the methods should be highly correlated with visual assessment, which means the measurements have to correlate with the visual sensation of the human observer.

The measurement of the optical properties of surfaces requires knowledge of their structure and their 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. Currently, none of these four issues are fulfilled in standard methodologies.

This European based research project aims to address those issues, in order to provide to the industry the measurement tools, methods and transfer artifacts, to characterize modern surfaces and ensure the traceability of the measurement to the SI-system and then a right, reliable and well-managed visual and instrumental correlation for industry.

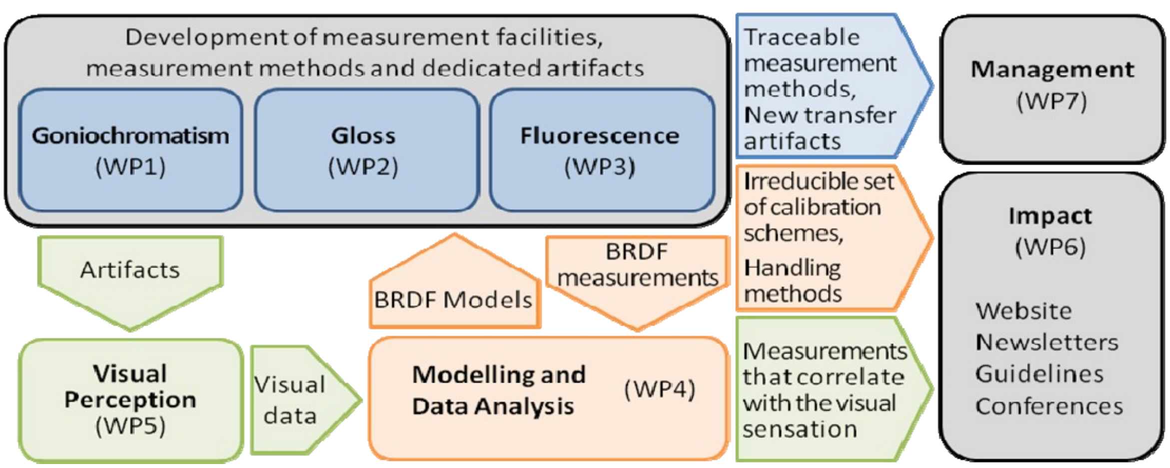

Figure 1. Structure of the project: The technical work packages WP1, WP2, WP3 deal with the describing and determining quantities of appearance (Color, Gloss, Fluorescence), WP4 provides data processing tools and the models. WP5 provides the visual scales. The results will create the impact of this project by knowledge transfer, training & dissemination and exploitation.

2. OVERVIEW OF THE SCIENTIFIC AND TECHNICAL OBJECTIVES

2.1 Goniochromatism

Common measurements in the classical field of reflectometry deal with the characterization of white, grey or colored standards, e.g. sintered polytetrafluorethylene (PTFE), opal glasses, barium sulfate pellets or ceramic tiles, typically in standardized geometrical configurations, e.g. diffuse irradiation and detection along the surface normal (d:0°) or directional irradiation under 45° with subsequent detection along the surface normal (45°:0°). However it has been shown that even for these so-called ideal standard materials, the reflection behavior 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 β extreme deviations of up to 385 % were observed [6]. 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 color communication and inefficiency; also currently, it is possible that good quality products may be needlessly rejected. Thus, the 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 realized 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 bidirectional 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 per mill 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 artifacts for the different types of modern surfaces, this improvement of measurement capabilities at the NMIs is mandatory. Furthermore, using photometric cameras, the spatial resolution is anticipated to be reduced from 20 mm to 20 µm [7]. This will not only enable the investigation of the homogeneity of standards, artifacts 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 blue and ultraviolet wavelength range of the spectrum.

Figure 2. Car painted with a goniochromatic varnishing, according to the visual perspective and the light conditions, the color impression changes

2.2 Gloss

Gloss is a visual attribute that is recognized as the second most relevant beside color, involved in the criterions of choice of an object, and is usually associated to quality and acceptability [8]. The most popular device that quantifies gloss is the glossmeter. This kind of 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 colors or between two different materials like e.g. velvet and plastic. Psychophysical experiments that have been conducted to characterize the visual perception of gloss show that the specular gloss correlates with the sensation of gloss only at a first order [9, 10]. The glossmeter is clearly not adapted to characterize subtle effects like the manufacturers in the field of cosmetics for instance, are used to dealing with. The glossmeter is not adapted because the visual system extracts gloss not only from the level of flux reflected in the specular direction but also from the shape of the specular peak itself [11].

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, like cosmetics or car painting industries for instance, a better knowledge of the shape of the specular peak according the direction of illumination and to the nature of the material is required. This work will be addressed in this research project.

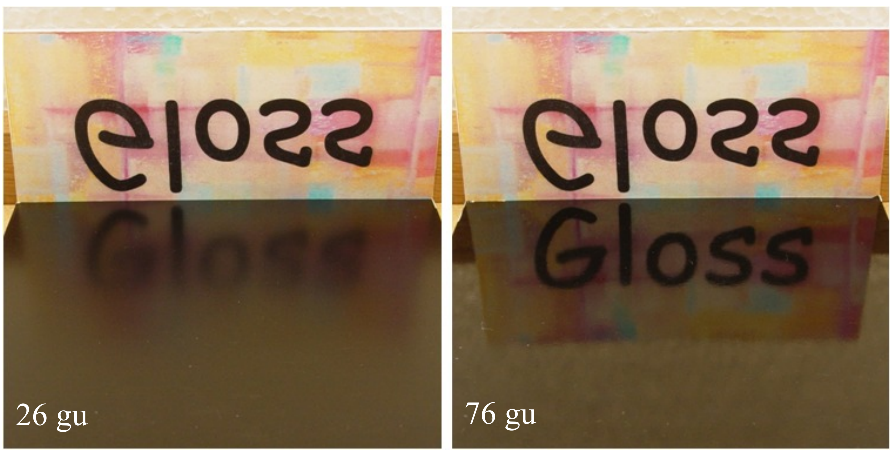

Figure 3. Example showing the visual appearance of two different black samples measured at an angle of 60° having gloss levels of 26 gu and 76 gu (gu: gloss units)

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 colored surfaces, as in car bodies [12]. 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 color instrumentation for the automotive sector.

But many unsolved questions are pending related to the viewing distance of sparkle in some measurement geometries, the influence of the illuminance level, the 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, in combination with 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 color difference (now related to many measurement geometries for goniochromatic materials) and the contribution of texture effects. The main purpose of many coloration industries, and specifically the automotive sector, is to have a reproducible and reliable method of assessing total visual appearance differences, which integrates color and texture, and correlates with visual and instrumental data, for improving quality control of their products.

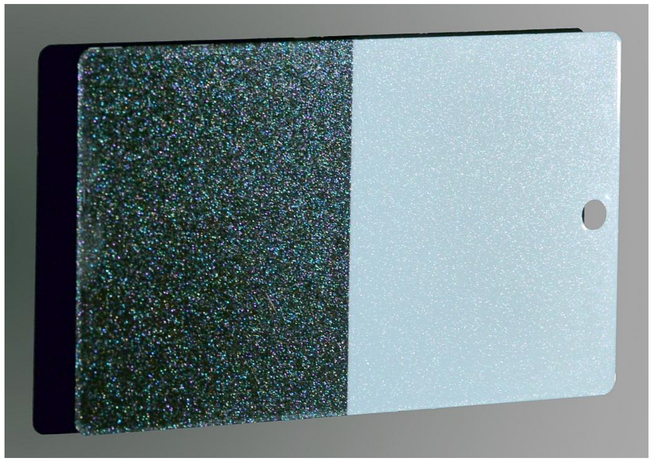

Figure 4. Special effect pigment Xirallic® Crystal Silver of Merck KGaA applied on two different backgrounds, black (left) and white (right), show an intense rainbow colored sparkle effect under directional illumination

2.4 Fluorescence

In the field of fluorescence, most of the existing methods and standards for measuring functional materials have evolved from methods used for ordinary materials. However, the spectrophotometric measurement techniques used for these ordinary materials are inadequate for application to these modern functional materials. This is recognized 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 instrumentation industry has difficulties to develop instruments 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 those used in printing technology, the paint industry, and even in display devices technologies.

New types of reference artifacts needed for calibration and characterization of instruments used for measuring fluorescence diffuse reflectance materials will be identified during 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 the luminescent radiance factor of fluorescence standards [13].

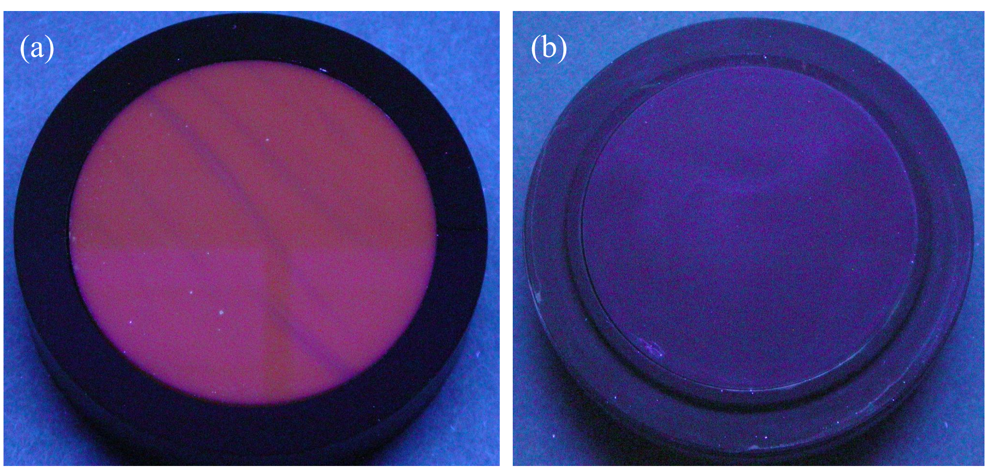

Figure 5. Photos of two different opal glass reflection standards under UV irradiation at 365 nm, (a) is a poor-quality standard showing an intense inhomogeneous orange fluorescence, (b) is a high-quality standard appearing with a black surface indicating the absence of fluorescence

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 transmittance distribution function (BTDF) and the full measurements in 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 gonioreflectometry.

The handling of these data needs to be addressed and handled properly. The establishment of a formalism to select the opportune angular configurations, to organize 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 highly required. These points will be addressed in this joint research project.

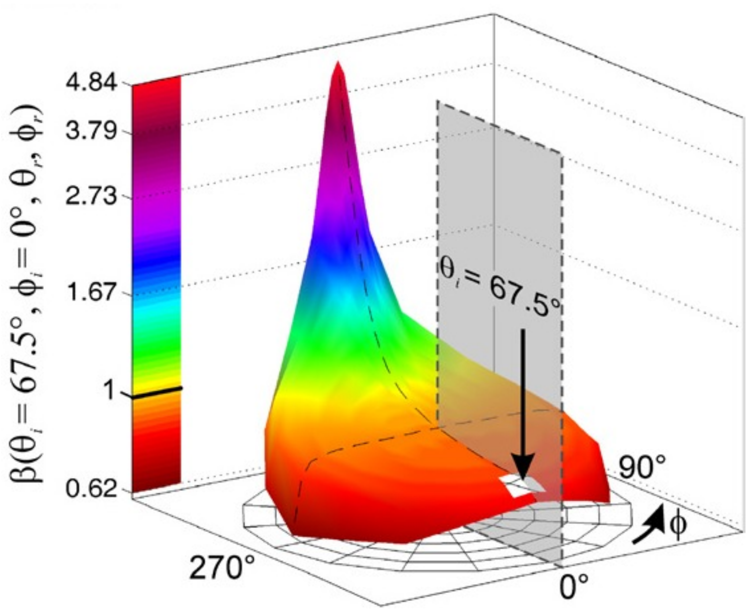

Figure 6. False color data representation of a full three-dimensional reflection indicatrix showing the radiance factor β of a Spectralon reflection standard at an incident angle of $\theta_i = 67.5°$ at a wavelength of $\lambda = 550$ nm

2.6 Vision

In industries where the appearance of the product is crucial, i.e. car painting or cosmetics, the characterization and the quality control of the product is still performed by trained human observers. The ISO 9000 framework, however, requires that whenever 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, if we want industries to use the instrumentation and methods developed in this project and switch from the traditional visual observation method to an instrumental-based method, it is essential that the measurements provided correlate with the perceptual response [14, 15]. The subject of the correlations between physical and perceptual measurands and the metrological evaluation of the uncertainties in the field of human perception will be treated in this project.

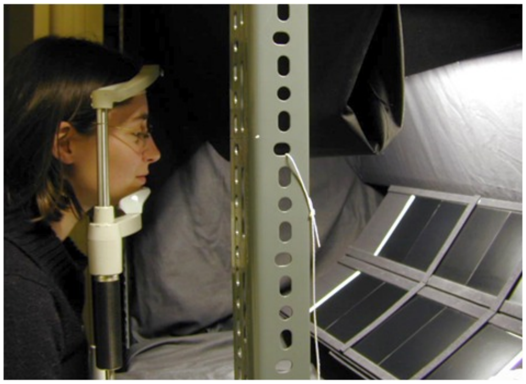

Figure 7. Observer performing a psychophysical experiment in a controlled environment

3. PROJECT PLAN OF THE GONIOCHROMATISM WORKPACKAGE (WP1)

3.1 Overview

There are a variety of new goniochromatic materials which have strong angular dependent reflection behavior. They show a color impression that depends on the spatial arrangement of illumination and observation relative to the surface of the artifact. The goniochromatic colors are produced based on the interference effect in which the incoming light is partly reflected from the particle surface and partly refracted through it. Depending on the coating thickness and variation of the angle of incidence of the applied radiation, a colorful appearance of the reflected light at various spatial directions is produced.

So far, however, goniochromatic pigments and paints are a problem for metrology as their color, saturation and brightness all change with visual perspective and the ambient lighting conditions. In the following the five main tasks of the goniochromatism workpackage are described.

3.2 Task 1: Improvement of the traceability for standard goniometric geometries

For hemispherical-directed reflectance which is measured by means of integrating spheres there are comparison results from an international Key-Comparison of the BIPM (Bureau International des Poids et Mesures), denoted as CCPR-K5 "Spectral diffuse reflectance" [16]. In the field of gonioreflectometry there is currently no international comparison dedicated to a set of standard geometries for bidirectional reflection.

The aim of Task 1 is to characterize the existing measurement facilities of the participating project partners in order to strengthen the traceability of BRDF measurements of goniochromatic surfaces and to reduce the uncertainty of the measurement. The validation will be provided via inter-laboratory comparison of these facilities in the wavelength range 380 nm to 780 nm, the V(λ)-region of visual appearance. The results given by the different instruments located at the institutions of the members of the consortium for a dedicated set of reflection standards (white and grey standards and also color standards) will be compared. From those results, and the measurement uncertainty budget for every instrument, uncertainties and systematic errors will be analyzed.

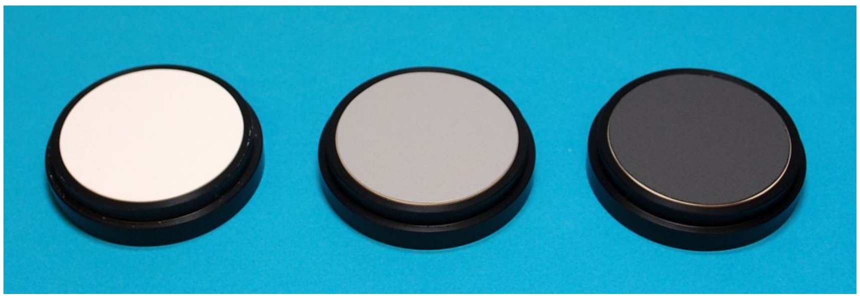

Figure 8. Diffuse matt ceramic grey scale standards, containing three different reflectances of 88 % white, 40 % grey and 5 % deep grey

Figure 9. Diffuse matt ceramic color standards, containing three different colors, red, green and blue

3.3 Task 2: Extensive study of existing standard materials (multi-geometry, extended wavelength)

Industrial needs of multi-geometry reflection measurements are not limited to the spectral range between 380 nm and 780 nm where the human eye is sensitive. Relevant for industrial applications is also the neighboring close-by spectral range between 200 nm to 2500 nm.

The aim of Task 2 is the measurement of the angular distribution of the spectral radiance factor or the BRDF of existing diffuse standard reflection materials within the extended wavelength range mentioned above, exceeding the limitations of photometric applications.

The basis for the description of the angular behavior of diffuse reflecting materials is the concept of the radiance factor β or the bidirectional reflectance distribution function f_r (BRDF). Both characterizations can be traced back to the concept of the perfectly reflecting diffuser, which reflects incoming radiation loss-free, completely diffuse and with a Lambertian direction characteristics. In fact there is no such material existing corresponding to this concept. For practical reasons radiance factor measurements are predominantly accomplished relative to commercially available reflection standards. From initial studies and measurements, clear indications of strongly non-Lambertian behavior of standard reflection materials emerged [17]. More detailed angle-resolved reflection data within the whole half-space above the standards (so-called multi-geometry configurations) are therefore needed as important reference for manufacturers, producers and users of radiometric and photometric products.

3.4 Task 3: Identification of a basic set of parameters for goniometric effects

There is currently only one commercial instrument on the market that is measuring a quantity called “sparkle index”. The definition and basis of computation of this quantity is not revealed. Also the correlation of this index as a pure number with the sensation of the human eye is unclear. Driven by these facts, extensive research for an open source and traceable sparkling index is necessary.

The aim of Task 3 is to find an irreducible set of scaling parameters for goniometric effects like lightness-flop, color-flop or sparkle/graininess.

3.5 Task 4: Data handling recommendation for goniochromatic materials

Data processing standards for BRDF measurements are 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 degrees of freedom to be controlled to reach every illumination/observation geometry plus its spectral dependency.

The aim of Task 4 is to establish a formalism in which to organize and manipulate efficiently the set of data acquisitions that represent BRDF measurements in order to quickly obtain information about symmetries in the sample.

Work is also required for the standardization 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 inhibit the efficient exchange of information. For the emerging “out-of-plane” geometries there are currently no agreed notations available.

3.6 Task 5: Database for impact work package (multi-geometry, wavelength dependent)

The aim of Task 5 is to create a database accessible by the scientific and industrial communities interested in goniochromatic effects. This database will contain categorized information relating to advanced surface materials, their goniospectrometric quantities and recommended measurement geometries for improved measurement traceability of their colorimetric characterization. Materials can be categorized by using different criteria. These criteria will be studied and selected afterward according to their relevance in industry.

4. INTER-LABORATORY COMPARISON OF STANDARD GONIOMETRIC GEOMETRIES

As mentioned in section 3.2 an inter-laboratory comparison of the different gonioreflectometer facilities realized by the project partners will be performed. The aim of this comparison is the improvement of the traceability for standard goniometric reflection geometries. The photo series below gives an overview of the variety of the different set-ups and measurement concepts. The facilities (a) to (d) are robot-based set-ups where the device under test is mounted to the robotic-hand of small industrial robots, giving the flexibility for arbitrary orientation in three-dimensional space [18-20].

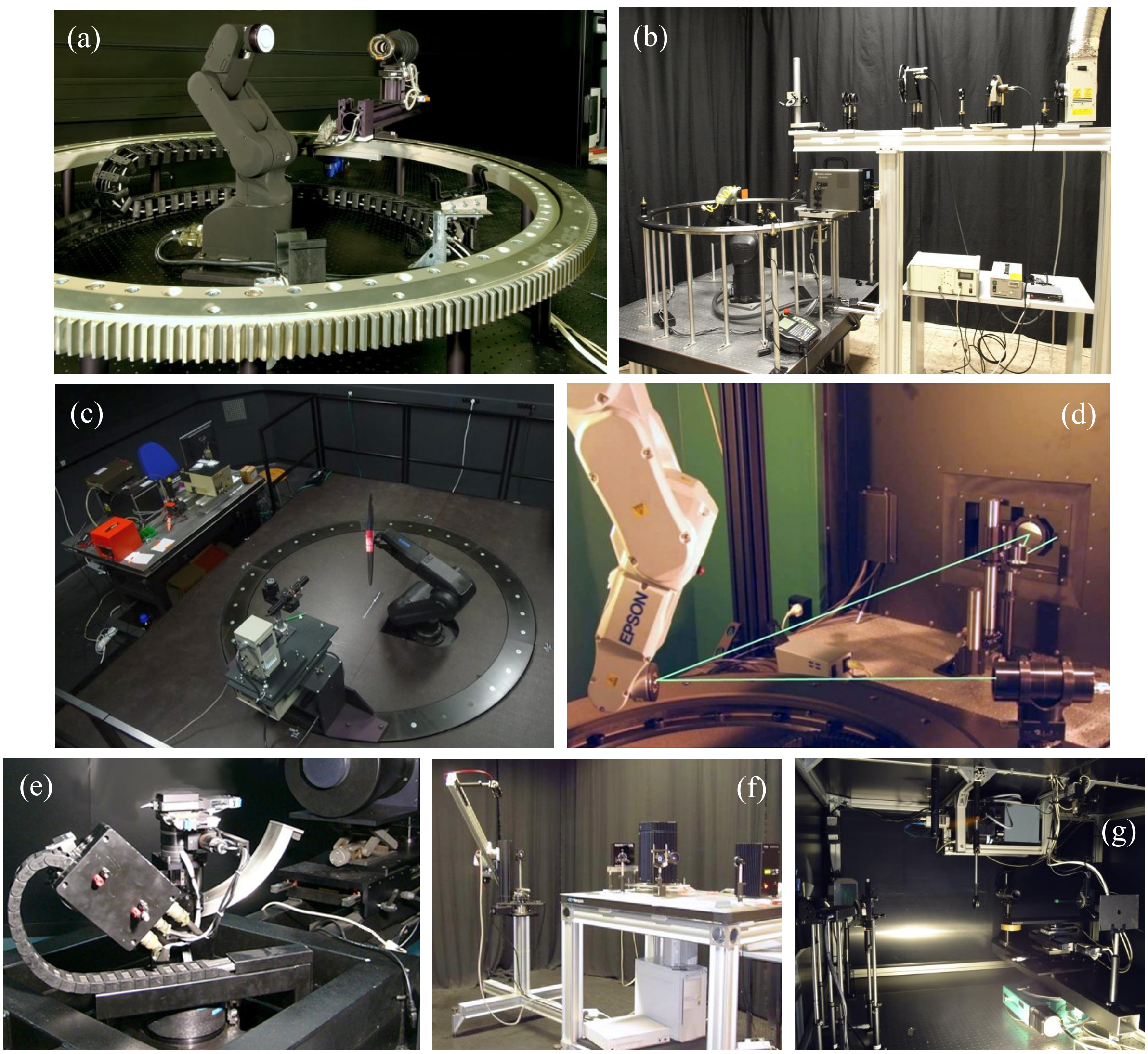

Figure 10. Photos showing the different gonioreflectometer facilities of the participating project partners: (a) robot-based gonioreflectometer at PTB, (b) facility at CSIC (Spain), (c) facility at CNAM (France), (d) facility at MSL (New Zealand), (e) facility at INRIM (Italy), (f) facility at Katholieke Universiteit Leuven (Belgium), (g) facility at MIKES (Finland)

The facilities (e) to (g) are built by mounting different rotation and translation stages together in order to realize the required degrees of freedom for the measurement of the devices under test [21, 22].

The comparison of the ceramic reflection standards (white/grey and colored standards) is organized as a star-type comparison, where the samples are first measured by PTB as the pilot lab, than measured by the participating lab, followed by a re-measurement at PTB for the sake of elimination of sample drifts. This scheme is repeated for every participant, where two pairs of sets of white/grey and colored standards are used. The comparison is performed in 0°:45° and 45°:0° geometry in the wavelength range 380 nm - 780 nm. The geometries are chosen because of their widespread use in commercial spectrophotometers.

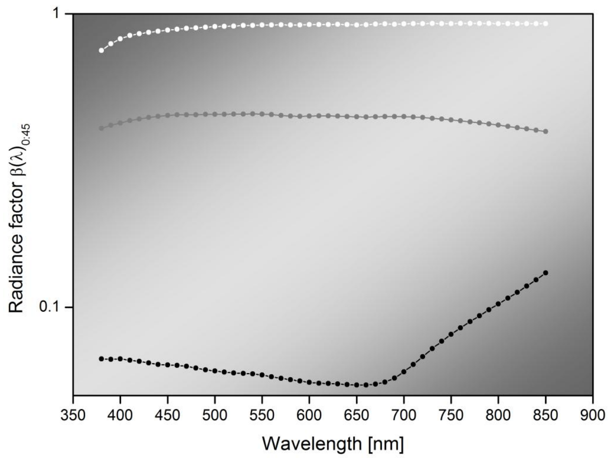

Figure 11. Spectral radiance factor of diffuse matt ceramic standards of nominal reflectances of 88 %, 40 % and 5 % in 0°:45° geometry in the wavelength range 380 nm to 780 nm in logarithmic representation

For the comparison a selection of three white/grey ceramic reflection standards with nominal reflectances of 88 %, 40 % and 5 % are chosen in order to be able to check the linearity of the different set-ups. The graphs in Figure 11 give an overview of the spectral dependence of the radiance factor of the different samples.

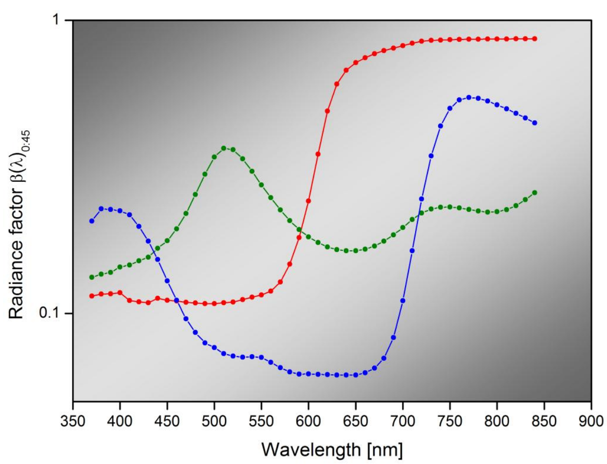

Figure 12. Spectral radiance factor of colored diffuse matt ceramic standards (red, green, blue) in 0°:45° geometry in the wavelength range 380 nm to 780 nm in logarithmic representation

For the comparison of colored ceramic reflection standards a selection of three samples with the colors red, green and blue are chosen in order to have different spectral dependencies and check the set-ups for wavelength correctness. The graphs in Figure 12 give an overview of the spectral dependence of the different samples.

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