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Effect of light scattering from source optics in goniometric diffuse reflectance measurements

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Abstract
The significance of light scattering around the main beam in a gonioreflectometer based measurement of spectral diffuse reflectance is discussed. This kind of scatter is always present in goniometric measurement systems that use a shaped measurement beam. Furthermore, errors due to this effect are a potential cause of discrepancies between goniometer and integrating-sphere based measurement methods. Procedures used to determine such errors and the required corrections are presented. At the Helsinki University of Technology, the determined wavelength-dependent correction in the worst case was as high as -1.6% and could be reduced to -0.2% with improvements in the optical setup of the gonioreflectometer. The measurement results for our diffuse reflectance reference materials with the appropriate corrections in each case are in good agreement, which gives a new view on some measurements reported earlier.

1. Introduction

Spectral diffuse reflectance measurements are usually performed relative to a reference standard traceable to an absolute scale. The absolute scales of directional-hemispherical reflectance are mainly based on integrating-sphere techniques [1–3]. An alternative method is the angular integration of goniometric measurement results [4, 5]. Goniometric measurement techniques are becoming more popular at national metrology institutes for the realization of absolute scales of spectral diffuse reflectance [6–9]. However, some discrepancies between the gonioreflectometric and the integrating-sphere based methods have been reported, thus raising questions about the origin of the deviations [7].

A gonioreflectometer was designed and constructed at Helsinki University of Technology (TKK) in 2004 [8]. Some problems with the measurement beam were encountered because of astigmatism caused by the monochromator. There was strong wavelength-dependent scattering of light about the main beam and a correction factor was needed to take care of the problem.

As a result of some modifications in the light-source system and beam imaging optics of our measurement setup, the spatial properties of the measurement beam have changed. The most important outcome is the changed correction required to account for the light scattered about the main beam. This source of error is under control in our gonioreflectometer, which is proved by the good reproducibility of the test measurement results presented in this paper. Due to inherent scattering properties of optical components, this kind of effect is always present in goniometric measurement systems using shaped measurement beams. If such effects are not properly accounted for, significant deviations may occur.

2. Measurement setup

The gonioreflectometer at TKK is illustrated schematically in figure 1. The sample is illuminated at fixed angles and the reflected light can be measured over the polar angles in the horizontal plane. The total diffuse reflectance is determined

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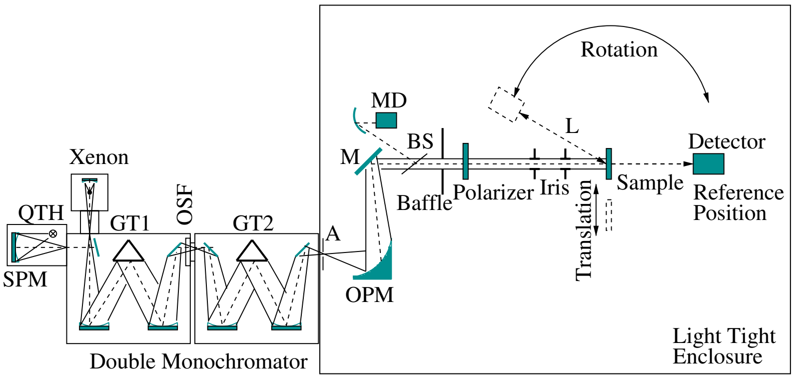

Figure 1. Schematic of the gonioreflectometer setup: QTH, quartz–tungsten–halogen lamp; xenon, xenon lamp; SPM, spherical mirror; GT1, GT2, grating turrets; OSF, order-sorting filter; M, flat mirror; A, aperture; OPM, off-axis parabolic mirror; BS, beam splitter; MD, monitor detector; L, distance between sample and detector.

(This figure is in colour only in the electronic version)

by integrating the measured angular distribution of the reflected flux with a 5° step over the hemisphere.

The measurement setup comprises a source system and a goniometric detection system in a light-tight enclosure. The main components of the source system are a quartz–tungsten–halogen lamp, a xenon lamp and a double monochromator. The halogen lamp output intensity becomes very small below 400 nm and the xenon lamp is used for reliable results, particularly at large measurement angles. The output beam is collimated and directed towards the sample by an off-axis parabolic mirror and a flat mirror. A thin quartz glass sheet beam splitter channels a fraction of the beam to a monitor detector for correcting the effects of possible light-source instability. The rest of the beam propagates through a polarizer and two irises before irradiating the sample. The reflected light is probed by the detector over a range of polar angles selected by the detector turntable. The full intensity of the incident light is measured at the reference position of the turntable (figure 1). During this measurement the sample is moved out of the beam path by using a linear translator. The sample is positioned on another turntable, coaxial with that rotating the detector, which allows adjustment of the angle of incidence of the beam. A thorough description of the measurement system, alignment process and the measurement procedure is given in [8].

The original setup as presented in [8] utilized a double monochromator having an astigmatism problem that had to be corrected by an additional flat mirror and a spherical mirror in the output optics (2004). In the second modification (2005), the monochromator was shortly replaced by a completely new one with toroidal mirrors, thus making it possible to simplify the output optics as an astigmatism correction was no longer needed. Following a successful change of spherical mirrors in the first (original) monochromator for toroidal ones, the original monochromator was put in service again in 2006. That was the third modification of the gonioreflectometer setup.

3. Definitions

With the gonioreflectometer at TKK we measure bidirectional reflectance (radiance) factors [8]:

$$\beta(\theta) = \frac{\Phi(\theta)}{\Phi_{\mathrm{i}}} \frac{4L^2}{D^2 \cos\theta}, \tag{1}$$

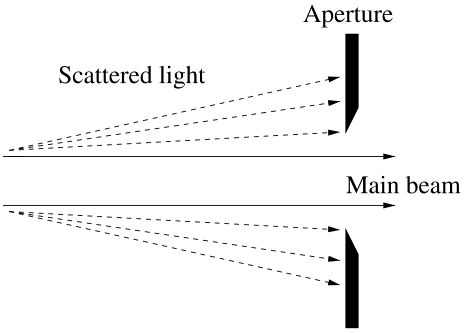

Figure 2. Light scattering around the main beam.

where θ is the viewing angle, $\Phi(\theta)$ is the measured reflected radiant flux in direction θ in a cone limited by the detector aperture (diameter D) at distance L from the reflecting surface and Φ_{i} is the measured incident flux. The total (directional-hemispherical) reflectance of the sample, R, is then obtained by integrating over the whole hemisphere assuming cylindrical symmetry in the azimuthal direction:

$$R = \int_0^{\frac{\pi}{2}} \beta(\theta) \sin(2\theta)\, \mathrm{d}\theta. \tag{2}$$

Due to requirements set by the measurement geometry, the beam has to be shaped by the output optics to cover a considerable distance. Hence it is difficult to maintain the same distribution of scattered light around the main beam and sharp edges along the whole propagation distance from the output optics to the sample. Moreover, the physical position of the incident flux measurement is still further away from the sample position by a distance L as indicated in figure 1. Hence the fraction of light scattered around the main beam may be different at the two positions (sample position and the position where the incident flux is measured). Thus the measurement intended to account for the incident flux which is reflected by the sample may miss the part of it spilling beyond the aperture edge as depicted in figure 2 and briefly discussed in [10]. This is the case for all measurement facilities that use shaped measurement beams.

Due to this effect the real radiant flux on the sample, $\tilde{\Phi}_{\mathrm{i}}$, may differ from the measured value, Φ_{i}. The relative difference of the measured and the real incident flux is the correction factor $f_\mathrm{c} = \frac{\Phi_\mathrm{i}}{\tilde{\Phi}_\mathrm{i}} - 1$. When Φ_i is replaced by $\tilde{\Phi}_\mathrm{i}$, equation (2) becomes

$$\tilde{R} = (1 + f_\mathrm{c}) \int_0^{\frac{\pi}{2}} \beta(\theta) \sin(2\theta)\, \mathrm{d}\theta. \tag{3}$$

Therefore, to take this possible source of error into account one only needs to measure the spectral correction factor, f_c, and apply it to the measured diffuse reflectance values.

4. Correction procedures

In all the setups in the years 2004, 2005 and 2006, the amount of light scattered about the main beam is in principle different, therefore resulting in different correction factors. This kind of correction is not usually necessary in a sphere-based diffuse reflectance measurement because of the different geometry of the measurement system. However, in a gonioreflectometric measurement the scattering increases the measured reflectance factor values if it is not accounted for.

Previously this kind of error has been investigated by using different sizes of apertures and by blocking the direct light [10]. In our measurement system we have used two slightly different methods to measure the correction factor. The first method measures spectral intensity at the sample and at the reference positions (figure 1) and compares the signal readings. For this measurement the whole detector package [8] in the measurement system has been used. The second method uses a simple detector with a similar lens (diam 50 mm) and aperture (diam 25 mm) as in the detector package of the measurement system. The aperture is positioned at the reference position of the setup approximately at the same distance from the sample as the aperture in the detector package. The lens is placed after the aperture and the detector is positioned at the focal point of the lens. Spectral intensity is measured both with and without the aperture and the corresponding readings are compared. The second method could be realized using the same detector package that is employed in the diffuse reflectance measurements but because of difficulties in removing the aperture in front of the lens, another lens and an aperture of the same size were used.

The two methods yield the same result for the correction factor. The advantage of the second method is that the effects of varying beam uniformity as well as misalignment or beam spot size are eliminated. This makes the measurement uncertainty slightly smaller compared with the first method. The disadvantage is that the second method is capable of estimating the scattered light only over a limited area (defined by the clear aperture of the lens used) around the main beam. The area limitation was exceeded in 2004 and the first method was applied. In 2005 and 2006 the correction became considerably smaller and it was possible to apply the second method.

5. Results

Figure 3 illustrates the different correction factors measured in the different setups during 2004–2006.

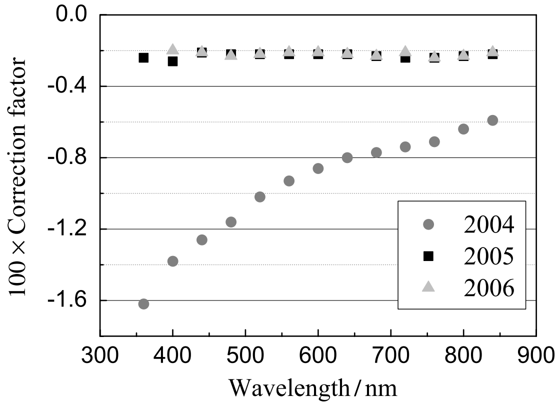

Figure 3. Correction factors in the different setups during the years 2004–2006.

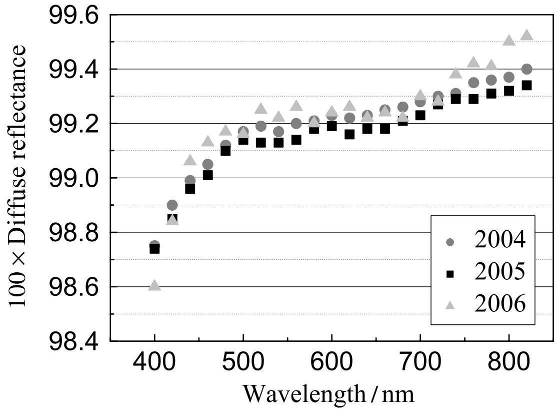

Figure 4. Spectral diffuse reflectance (directional-hemispherical) of a white Spectralon sample measured with the different setups during the years 2004–2006.

The measured correction factors are very similar in the years 2005 and 2006, which suggests that the optical components in the monochromator and the respective beam preparation optics greatly determine the magnitude of the required correction. Both monochromators from 2005 and 2006 are also quite similar; they make use of toroidal mirrors and the same beam shaping optics is employed. Therefore the scattering of light about the main beam can be expected to be similar in those cases. In 2004 the correction was significantly larger, which suggests that the scattering of light could lead to significant errors in the measurements if it is not accounted for.

To validate the performance of the instrument after the changes in the source system, test measurements were performed. Figure 4 presents $0/d$ reflectance of a Spectralon sample measured with the different setups in 2004, 2005 and 2006. Agreement between the measurements with the different setups is well below 0.2%, which is the uncertainty of the scale realization. This suggests that light scattering is well under control in our measurement system. Furthermore the repeatability and reliability of the device is very good.

6. Discussion

Due to inherent scattering properties of optical components, the scattering of light about the main beam may turn into a significant, or at least not negligible, source of error if not accounted for. This effect will cause problems in all facilities using shaped measurement beams [6–8]. The correction must be applied unless beam properties (collimation, astigmatism, etc) are nearly perfect.

When designing and characterizing a high-accuracy gonioreflectometer, it may be useful to have a way to easily check the magnitude of the correction. A simple but not very reliable method is to take a piece of white paper and visually inspect the surroundings of the main beam. If the beam is diverging slightly and the scattered light stays close to the main beam, this should be visible to the naked eye. It also indicates that the required correction is probably not very big. However, if the light beam is strongly scattering around the main beam, it may be difficult to observe with just a piece of paper. Furthermore, this kind of visual inspection is not objective and therefore not very reliable. A more reliable way to check for this kind of scatter could be to use a sphere detector. The sphere should be positioned so that the light goes straight through and the output port is situated approximately at the aperture position of the detection system. The output port should be of the same size as the aperture. If the light is scattering around the main beam, some of it doesn't get out of the port, hits the sphere walls and contributes to the sphere detector signal.

A preliminary inspection of the scattering correction may help in determining which way the correction factor should be measured. For example, if the required correction is found to be small, the correction can be measured in a similar way to the second method described in section 4.

7. Conclusions

Some modifications have been made in the light-source system of the gonioreflectometer at TKK, leading to different spatial properties of the measurement beam. The amount of scatter about the main beam in three modified setups varied from about -1.6% to -0.2%. Since the agreement between measurement results over a period of three years while improving the setup and determining the correction factor for each modification is very good, we believe that the scattering of light about the main beam has been properly accounted for. Furthermore, this effect might be one of the reasons for the discrepancies reported previously between measurements based on the gonioreflectometric and integrating-sphere techniques [7].

Due to the inherent scattering properties of optical components this problem is always present in goniometric facilities which use a shaped measurement beam. Considering the magnitude of the correction required before the modifications, it is obvious that definite errors will occur if light scattering about the main beam is not taken into account when designing and characterizing such a gonioreflectometer.

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