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What is the Reddening Effect and does it really exist?

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Abstract

The simulation of light-matter interaction is a major challenge in computer graphics. Particularly challenging is the modelling of light-matter interaction of rough surfaces, which contain several different scales of roughness where many different scattering phenomena take place. There are still appearance critical phenomena that are weakly approximated or even not included at all by current BRDF models. One of these phenomena is the reddening effect, which describes a tilting of the reflectance spectra towards long wavelengths especially in the specular reflection. The observation that the reddening effect takes place on rough surfaces is new and the characteristics and source of the reddening effect have not been thoroughly researched and explained. Furthermore, it was not even clear whether the reddening really exists or the observed effect resulted from measurement errors. In this work we give a short introduction to the reddening effect and show that it is indeed a property of the material reflectance function, and does not originate from measurement errors or optical aberrations.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Three-Dimensional Graphics and Realism—Color, shading, shadowing, and texture

1. Introduction

In computer graphics the simulation of light-matter interaction is a major challenge. Often, it is described by an analytical formulation of physically based Bidirectional Reflectance Distribution Functions (BRDF). These BRDFs are based on physical parameters, and model the surface reflectance in a physically plausible manner.

Analytical BRDFs are designed on the basis of real world observations or physical measurements, and BRDF datasets, such as the well known MERL database [MPBM03], are of important value. Nevertheless, in these datasets the whole spectrum of visible light is represented by three RGB values. To model wavelength dependent scattering phenomena on the basis of this information is very hard or even impossible.

Current BRDF models have lead to photorealistic images but often fail to be predictive, especially for rough surfaces. Those surfaces contain several different scales of roughness where many different scattering phenomena take place. This configuration makes this type of surface particularly challenging to model properly.

To improve the predictive rendering of rough surfaces we conducted in a previous work [CMF18] a spectral comparison between a real and a simulated scene, where the reflection behaviour of all materials of the real scene are represented by a Cook-Torrance BRDF with a GGX distribution fitted against measured spectral data. The comparison showed that the used BRDF model was incapable of representing all appearance critical scattering phenomena of rough surfaces, which lead to deviations between reference and predicted data.

During the analysis of the fitting error we observed a strong linear wavelength dependency of the reflectance spectra especially at grazing incident and viewing angles, which is not included in the used BRDF model and, consequently, results in a bad fitting. To the best of our knowledge there is no BRDF model that includes this phenomenon.

Only the work by Levesque et al. [LD16] made the same observations as us during measuring the in-plane BRDF of Spectralon. They call the tilting of the reflectance spectra towards long wavelengths the reddening effect. Although there are two independent works observing the reddening effect, we are still not sure whether the reddening effect really exist. The linear behaviour of the reddening effect is from a physical point of view unusual and the explanation given by Levesque et al. is insufficient. Furthermore, a similar behaviour can be observed when measuring the BRDF of very smooth materials, which can be traced back to optical aberrations of the detector. It could lead to the assumption that the observed reddening effect is also caused by lens aberrations, due to rough surfaces acting like a mirror under grazing incident and viewing angles. Therefore, in this paper we will further investigate the

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reddening effect and confirm its existence, discarding the optical aberration and the measurement error possibilities.

2. Related Work

To analyze the wavelength dependent reddening effect, spectrally resolved BRDF data are necessary. There are several databases of measured BRDFs [DJ18, MPBM03, FV14, FVH14], yet only Dupuy and Jakob [DJ18] provide spectrally resolved data. Moreover, the works by Levesque and Dissanska [LD18] and Durell et al. [DSM*15] provide spectral BRDFs of the white reflectance standard Spectralon by Labsphere.

Durell et al. [DSM*15] conducted a round robin test where four laboratories acquired the BRDF at defined positions and wavelengths of two Spectralon samples. Each laboratory received their own two Spectralon sample by the authors. They conclude that two laboratories produced nearly identical values, even though they had different samples and measuring devices. The other two laboratories produced data that was not entirely in accordance with those previous two, but could be adjusted in some trivial way (such as scaling) to conform. The authors then propose the average of the two first laboratories as the reference Spectralon BRDF.

Dupuy and Jakob [DJ18] propose a new efficient BRDF parameterization that automatically adapts to the scattering characteristics of the material, where important regions are sampled densely, while negligible regions are compressed. Furthermore, they published a steadily growing database of spectral BRDFs, which contains, among others, the BRDF for a Spectralon sample. However, in our work a newly acquired Spectralon BRDF provided by Wenzel Jakob [Jak19] is used to avoid any chances of error introduced by the processing of the raw measured data as described in [DJ18].

Levesque and Dissanska [LD18] propose a Spectralon spectropolarimetric BRDF model. They densely acquired the spectral in-plane Spectralon BRDF as a function of the polarization direction, which is used to determine the BRDF model.

3. The Reddening Effect

The reddening effect was first observed and investigated by Levesque et al. [LD16] in 2016, and again reported by us in 2018 [CMF18]. It can also be observed in the BRDF data published by Dupuy et al. [DJ18], even though it is not clear if they were aware of such effect as it is not mentioned in their work.

The reddening effect describes a tilting of the reflectance spectrum towards long wavelengths. It is notable on rough surfaces especially in the specular reflection, and increases with the incident angle. The reddening effect is principally polarized in “S”.

Levesque et al. [LD16] trace the reddening effect back to Rayleigh scattering, which takes place on the surface. In their definition the surface is a function of the wavelength. At short wavelengths the surfaces acts as a diffuser and at long wavelengths as a mirror. However, the Rayleigh scattering depends on $\frac{1}{\lambda^4}$ [Ban06, p. 186]. This non-linear wavelength dependency contradicts the linear wavelength dependency observed at the reddening effect.

The observation of the reddening effect at rough surfaces is new

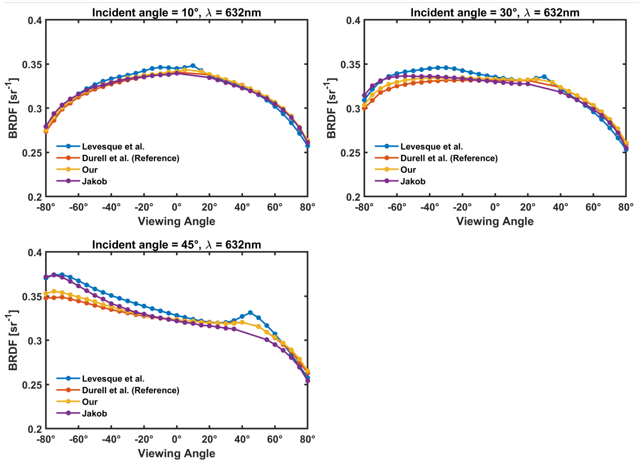

Figure 1: *Spectralon BRDF for wavelength 632 nm and three incident angles* 10°, 30°, *and* 45° *acquired by Levesque et al., us, and Jakob compared to the reference BRDF provided by Durell et al..*

and the characteristics and cause of the reddening effect have not been thoroughly researched and explained. It is still not absolutely clear whether the reddening really exists or results from measurement errors. Therefore, in a first step, a cross validation of the used gonioreflectometer is necessary to ensure that the reddening effect does not originate from measurement errors.

4. Evaluation of the Gonioreflectometer Setups

To evaluate the fidelity of the gonioreflectometers used by Levesque et al., Jakob and us, the Spectralon BRDFs are compared to the reference data published by Durell et al.. Figure 1 shows these plots for wavelength 632 nm for the viewing angles -80° - 80° and the incident angles 10°, 30° and 45°. The figure demonstrates that our BRDF data are in great accordance with the reference data, which proves the high fidelity of our gonioreflectometer. Levesque’s and Jakob’s data are in line with the reference data for small incidence angles, while with increasing incident angles deviations in the forward scattering can be observed. These deviations probable originates from different Spectralon samples used by each laboratory. In Levesque’s case, we assume that a slightly smoother Spectralon sample was used, due to the higher specular reflection.

The evaluation shows that Levesque’s, Jakob’s and our gonioreflectometer are working reliable for the tested incident angles. Unfortunately, Durell et al. do not provide BRDF data for large incident angles, where the reddening effect can be observed. Nevertheless, to evaluate the gonioreflectometers for large incident angles and to investigate the reddening effect, in Figure 2 the BRDF spectra at an incident angle of 80° and viewing angles -50° - -80° acquired by Levesque et al., Jakob and us are compared. The Figure depicts, that the data by Levesque et al. agree well with our data for small viewing angles, but deviates for large viewing angles. These deviations are consistent with the assumption that Levesque et al. probably use a slightly smoother Spectralon sample. The cause of the deviations of Jakob’s data from the others is yet unclear. We

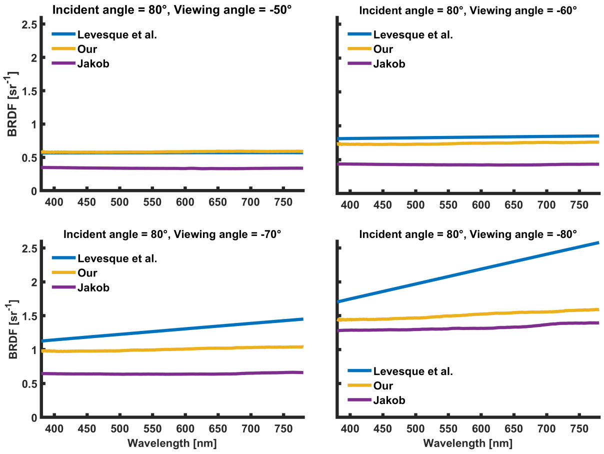

Figure 2: *Spectral BRDF of Spectralon at an incident angle of* 80° *and the viewing angles* -50°, -60°, -70° *and* -80° *acquired by Levesque et al., us and Jakob.*

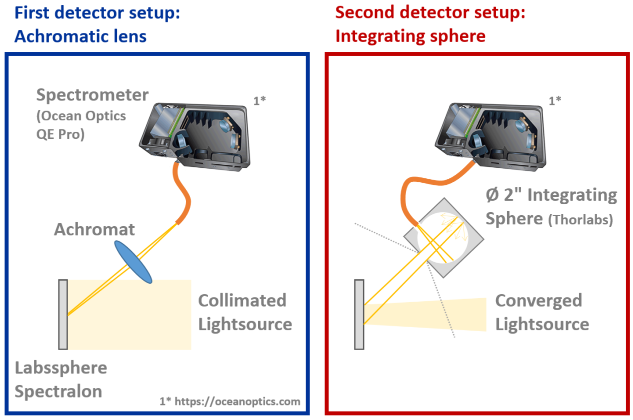

Figure 3: *Left: In the first detector setup the sample is illuminated by collimated light. The scattered light is captured and coupled into a fiber cable by an achromatic lens. The fiber cable is connected to an Ocean Optics Spectrometer. — Right: In the second detector setup the achromatic lens is replaced by an integrating sphere from Thorlabs and the sample is illuminated by converged light.*

are in contact with Wenzel Jakob to figure out the source of these deviations.

Despite the deviations, all three sources show a tilting of the reflectance spectra (reddening effect) especially at large viewing angles. Each of the three gonioreflectomters have a different measurement configuration and use different components, but all of them use a similar detector with a focusing achromatic lens, as shown in Figure 3. Thus, we can rule out the measurement errors as the source of the reddening effect. Nevertheless, we have not yet proven that the optical aberration is not the actual source.

5. Validation of the Detector

In order to exclude the achromatic lens as a possible source of error we conducted another Spectralon BRDF measurement with a modified gonioreflectometer setup, where the achromatic lens is replaced by an integrating sphere and the light source is converged instead of collimated. In Figure 3, the two gonioreflectometer setups are depicted. Our gonioreflectometer is designed for the standard setup, and that is why the modified setup has a lower angular resolution than the standard setup. Furthermore, for the modified setup a bigger Spectralon sample is necessary, hence, we used a larger white reflectance standard with a slightly smoother surface than the Spectralon sample.

In Figure 4 the BRDF spectra of the diffuse standard for an incident angle of -80° and the viewing angles $0^\circ - 80^\circ$ for the standard detector with the achromatic lens and the modified detector with an integrating sphere are shown. There are clear differences between the BRDF acquired by the standard and the modified detector. Especially at small viewing angles the BRDF spectra acquired with the modified setup are much higher than when acquired with the standard setup. These differences are caused by the different angular resolution of both setups. However, the shape of the spectra remain similar for the two setups, and both plots show the tilting of the spectra towards large wavelengths, i.e. the reddening effect, at large viewing angles. These observation clearly confirms that the reddening effect does not originate from optical aberrations of the achromatic lens.

6. Conclusions

In this work we gave a short introduction to the reddening effect, which describes a tilting of the reflectance spectrum towards long wavelengths, which takes place especially in the specular reflection and increases with the incident angle. Furthermore, we demonstrated that the reddening effect is indeed a property of the material reflectance function, and does not originate from measurement errors or optical aberrations.

Therefore, we first compared the Spectralon BRDF acquired by Levesque et al., Jakob, and us to the reference data provided by Durell et al. to evaluate the fidelity of the used gonioreflectometers. We concluded that our acquired Spectralon BRDF matches well the reference data, which confirms the reliability of our gonioreflectometer. The BRDF data of Levesque et al. and Jakob show with increasing incident angles small differences in the forward scattering, probably originated by different Spectralon samples. With the gonioreflectometers validation we could discard the reddening effect as a measurement error.

We next showed that the reddening effect can be observed in the Spectralon BRDFs acquired by Levesque et al., Jakob, and us, although three different gonioreflectometer are used. However, all evaluated gonioreflectometers use an achromatic lens to focus and couple the scattered light into a fiber cable. Hence, we acquired the Spectralon BRDF with a modified detector, where the achromatic lens is replaced by an integrating sphere. The new acquired BRDF also contain the reddening effect, which again confirms its existence and discards the lens aberration hypothesis.

As future work we plan to further investigate the reddening effect. In particular, we want to find out whether the reddening effect

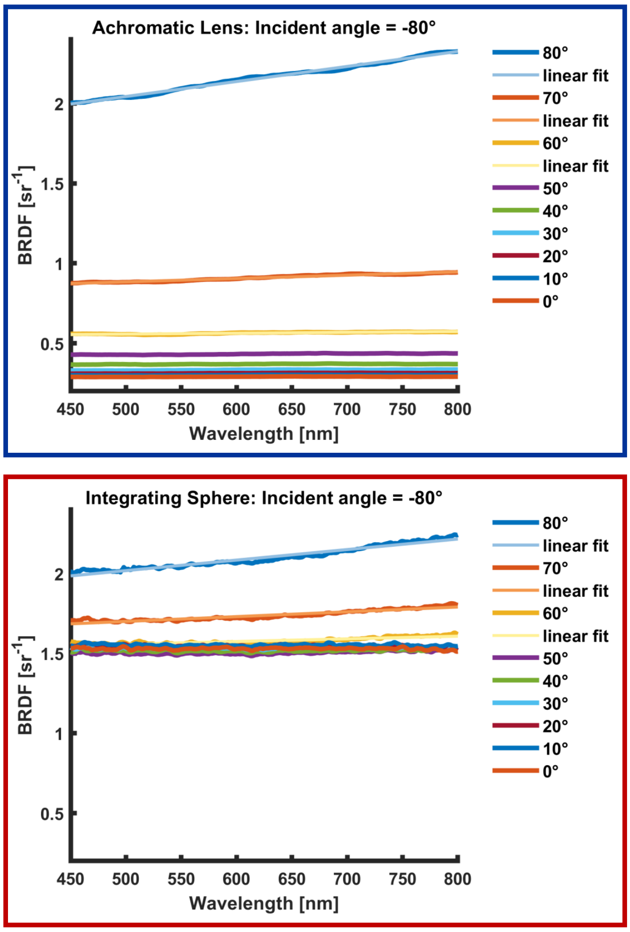

Figure 4: *Spectralon BRDF spectra at an incident angle of* -80° *and viewing angles varying from* 0° *to* 80° *acquired with the first (upper) and second (lower) detector setup.*

can be described as a function of the surface roughness. On the basis of our new insights we intend to develop a physically based BRDF model which includes the reddening effect.

7. Acknowledgments

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