

Article

Analysis of the Helmholtz Reciprocity Principle in Laboratory Practice

Maciej Skrzetuszewski ^{1,2,*}, Łukasz Litwiniuk ¹, Maciej Zajkowski ², Sylwia Górnik ¹ and Kateryna Hovorova ¹

¹ Electricity and Radiation Department, Central Office of Measures, Elektoralna 2 Street, 00-139 Warsaw, Poland; lukasz.litwiniuk@gum.gov.pl (Ł.L.); sylwia.gornik@gum.gov.pl (S.G.); kateryna.hovorova@gum.gov.pl (K.H.)

² Faculty of Electrical Engineering, Białystok University of Technology, Wiejska 45D Street, 15-351 Białystok, Poland; m.zajkowski@pb.edu.pl

* Correspondence: maciej.skrzetuszewski@gum.gov.pl

Abstract

The paper presents the results of the research on the spectral reflectance characteristics of colorimetric standards and the practical verification of the Helmholtz principle of reversibility of measurement geometries. The studies were conducted in the calibration laboratory of the Central Office of Measures (GUM) using a spectrophotometer equipped with a multi-angle accessory, enabling measurements over a wide range of angular configurations. Ceramic standards from the DM05 set, Teflon standards, and an enameled reference standard were analyzed. For each sample, measurements were performed in pairs of inverse angular geometries, $x^\circ:0^\circ$ and $0^\circ:x^\circ$, and then the relative deviations (differences between nominally reciprocal configurations) from the Helmholtz principle of reciprocity were determined. The studies provide a basis for a better understanding of the reflectance properties of the standards and for assessing the measurement capabilities of spectrophotometers operating in directional geometry.

Keywords: reflected light; Helmholtz reciprocity; spectral reflectance standards; spectrophotometer with multi-angle accessory; reflectance colorimetry; color space lab

1. Introduction

Calibration laboratories are the key players in maintaining the traceability chain in the fields of their specialization. The colorimetry laboratory at the Central Office of Measures uses reflectance standards as a reference in the calibration of spectrophotometers measuring reflected light in the visible spectrum [1–3]. In a world where color becomes the key to visual communication, colorimetry provides tools that allow for its objective description and control, and professional calibration creates a basis for achieving the required precision [4–7]. The calibration process itself requires not only advanced equipment but also sufficiently good color standards that ensure repeatability, reproducibility, and reliability of results [6–9]. The standards used at the Central Office of Measures to transfer units of measurement to reflectance spectrophotometers include standards from the “Glossy Ceramic Color Standards” DM05 set of ceramic reference standards, Teflon colored and achromatic standards, and enameled reference standards. All of them are fully characterized in terms of spectral reflectance values and feature good homogeneity of coloration [10–15].

Academic Editor: Mira Naftaly

Received: 17 June 2026

Revised: 22 July 2026

Accepted: 23 July 2026

Published: 24 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\) license](https://creativecommons.org/licenses/by/4.0/).

Measurements using colorimetric standards are performed in precisely defined measurement geometries, i.e., at specific angles of incidence and reflection of light [2,3,8–10]. The CIE (International Commission on Illumination) recommends the use of four basic variants: these include $0^\circ:45^\circ$, $45^\circ:0^\circ$, $8^\circ:d$ (where a sample is illuminated with a directed light source at an eight-degree angle, and the total reflected light is observed diffusely using an integrating sphere) and $d:8^\circ$ (the reverse of $8^\circ:d^\circ$) configurations (materials with high-gloss, metallic, pearlescent, and interference effects) [10]. However, limiting ourselves solely to a narrow range of one geometry does not allow for a complete picture of the reflective properties of the tested objects [16,17]. As previous studies have shown, a strong specular reflection signal causes disruption of the expected characteristics for the considered color standards [17]. The nature of the reflection—more specular or more diffuse—depends on the specific surface onto which the light falls [13,14,16–18]. A natural tool for characterizing reflection properties depending on the multi-angle measurement geometry is the technique based on the BRDF function (Bidirectional Reflectance Distribution Function) [1,18–20] using a spectrophotogoniometer. In our research, however, we decided to check the reciprocity of the geometries using a spectrophotometer with a multi-angle accessory. Using the possibilities offered by the spectrophotometer equipped with a multi-angle accessory, the authors of this paper conducted research aimed at supplementing the knowledge on both the extended characteristics of standards and the measurement capabilities of their research equipment [16–20]. However, the results of the following study—while pertaining to the broad field of multi-angle measurements involving reflected light—should be applied exclusively to measurements performed using the specific equipment (Cary 5000 with a multi-angle attachment UMA) and the specific standards used here, bearing in mind that these are not BRDF measurements.

The results of the studies for a wider range of reflection angles are presented here, with particular attention paid to the practical verification of the application of the Helmholtz principle of reciprocity of measurement geometries using various types of chromatic and achromatic standards [21,22]. The Helmholtz principle of reciprocity is a fundamental principle of optical physics, which states that the reflectance distribution function of a material remains unchanged if the incident light source and the detector are interchanged [21–24]. The Helmholtz reversibility principle is widely used in metrological laboratories worldwide for the measurement of reflected light [21–24]. The main problem with applying this principle is that due to the variety of devices and tested samples, deviations from this principle may differ and, consequently, the uncertainty of the result may have different values. Therefore, it seems reasonable to verify this principle in terms of the use of a given type of measuring equipment using specific measurement standards. An attempt was made to verify the applicability of this principle using measurement equipment available at the Central Office of Measures. The study aimed to examine the potential variability in the reflection characteristics of different types of standards used here, assuming the Helmholtz principle of measurement-geometry reversibility, and to assess possible deviations from this principle in close relation to the capabilities and limitations of the measurement system used here. This paper presents the initial phase of research aimed at verifying the Helmholtz reciprocity principle for the specific type of device and standards under consideration. At the same time, the authors recognize the need to further develop this work by establishing an appropriate uncertainty budget, which should eventually be compared with the obtained results to enable a more in-depth analysis. Nevertheless, the aim of this paper is to highlight interesting trends observed during these preliminary studies.

2. Materials and Methods

In this article, we present the full experimental details that allow for precise replication of the procedure and ensure transparency of the methodology. By outlining the rationale, conditions, and measurement strategy, we establish a clear foundation for interpreting the results and evaluating the reliability of the findings. A detailed full description of the experiment is provided below.

The angular characteristics of reflected light were measured using a spectrophotometer Cary 5000 UV-Vis-NIR (Agilent Technologies, Santa Clara, CA, USA) with a multi-angle accessory UMA (the Cary Universal Measurement Accessory). The light source was a tungsten halogen lamp (for the VIS range). The type of detector used in the experiment was the Si/InGaAs detector. During the tests, a detector aperture of only 3° was used. The choice of detector aperture was based on previous studies involving measurements of such standards using the same device [16,17]. The wavelength visible range used in all experiments described here was 400 nm to 700 nm.

Measurements were performed using selected ceramic and Teflon standards (Figures 1 and 2), as well as a HunterLab white enamel tile reference standard no. LX17112 (Figure 3).



Figure 1. Set of ceramic color standards (DM05) used during the experiment (pale gray, red, deep pink, orange, yellow, green, cyan, and deep blue).

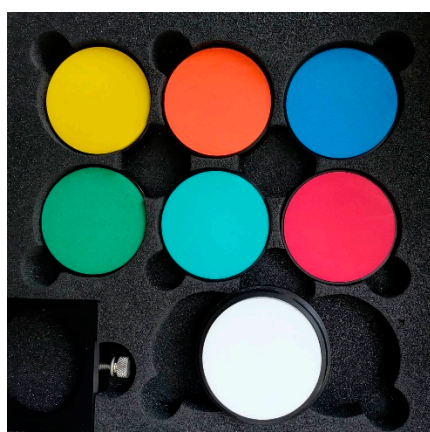


Figure 2. Set of PTFE color standards (7609F) and white PTFE standard (6194) used during the experiment.



Figure 3. White enamel standard no. LX17112 by HunterLab.

For the ceramic reference standards from the Glossy Ceramic Color Standards DM05 set (dimensions 102 mm × 102 mm and thickness 9 mm), the following tiles were selected for testing: pale gray, red, deep pink, orange, yellow, green, cyan, and deep blue. For the study of Teflon color standards, the following standards were selected: cyan, blue, red, yellow, green, orange (set no. 7609F, 5 cm in diameter), and the white Spectralon standard no. 6491. The Spectralon diffuse reflectance standard (5 cm in diameter) is made of sintered polytetrafluoroethylene (PTFE).

During the measurements, 7 corresponding measurement geometries were used, ranging from 15° to 75°, with 10° steps (15°:0°, 0°:15°; 25°:0°, 0°:25°; 35°:0°, 0°:35°; 45°:0°, 0°:45°; 55°:0°, 0°:55°; 65°:0°, 0°:65°; 75°:0°, and 0°:75°). A simplified measurement scheme of setups used in the tests is shown in Figure 4.

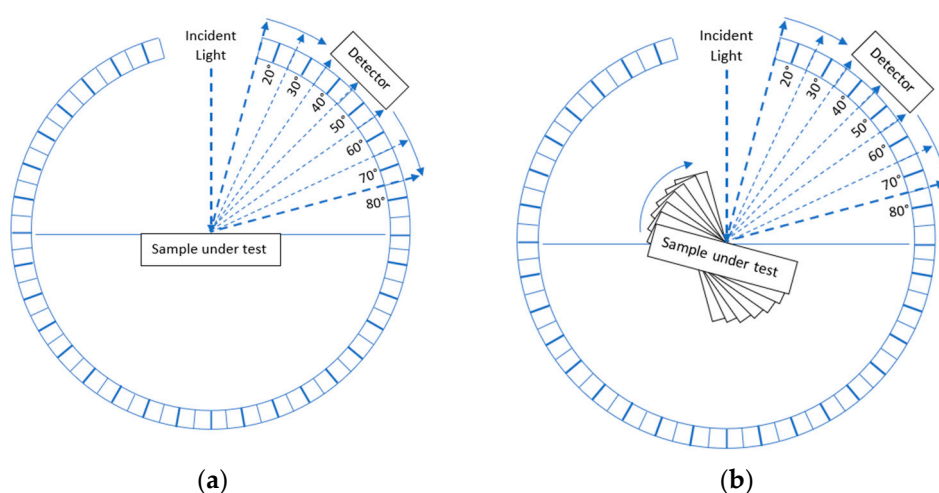


Figure 4. Measurement scheme of setups used in the tests. (a) Setups in measurement geometry 0°:x° (where x is the position of the detector: 15°, 25°; 35°; 45°; 55°; 65°; and 75°). (b) Setup in measurement geometry x°:0° (where x is the position of the sample: 15°, 25°; 35°; 45°; 55°; 65°; and 75°).

For example, a 15°:0° geometry setting means that the sample was positioned at a 15-degree angle relative to the incident beam (15° from the line perpendicular to the sample), and the detector recorded the reflected radiation at a reflection angle of 0° (the detector was positioned on an axis perpendicular to the sample surface). The measurement geometry was then changed to 0°:15°, meaning that the beam was incident perpendicularly to the sample, and the detector was positioned at a reflection angle of 15° (15° from the line perpendicular to the sample). This sequence was repeated for the variants mentioned

above. The sample and detector setup in one of the measurement geometries studied here, $45^\circ:0^\circ$ and $0^\circ:45^\circ$, corresponds to one of the CIE-recommended measurement geometries [10].

3. Results and Discussion

At the GUM laboratory, the Helmholtz reciprocity principle is used on a daily basis to transfer units of measurement from one measurement geometry to another. This principle applies to both spherical and directional geometries, for example, $8^\circ:d$ and $d:8^\circ$, as well as $45^\circ:0^\circ$ and $0^\circ:45^\circ$. The graph below (Figure 5) presents results obtained using spectrophotometers routinely used at the GUM for calibration of various spectral reflectance standards, which have reciprocal measurement geometries of $45^\circ:0^\circ$ and $0^\circ:45^\circ$. In this case, specialized devices dedicated to measurements in only one measurement geometry were used to verify Helmholtz's law:

- The first is $45^\circ:0^\circ$ (HunterLab ColorFlex), with illumination that is annular around the sample at an angle of 45° , ensuring the most uniform possible illumination of the sample,
- The second is $0^\circ:45^\circ$ (HunterLab LabScan), with incident illumination at an angle of 0° and reading the reflected beam at an angle of 45° .

The results were obtained for a reference standard: HunterLab white enamel plate no. LX17112. For the comparison, the spectral data from the NPL certificate results is also included. The results from the NPL certificate pertain to the same white enamel plate no. LX17112 that was calibrated using the same measurement geometry at $0:45$ at the National Measurement Standards Laboratory of the United Kingdom (National Physical Laboratory (NPL)).

As illustrated in the graphic, the ordinate axis shows the spectral radiance factor R (value expressed as a percentage), while the abscissa axis indicates the wavelength range (400–700 nm). Additionally, using the secondary axis, Figure 5 shows the differences between measurements performed on different devices (symbol Δ on the graph).

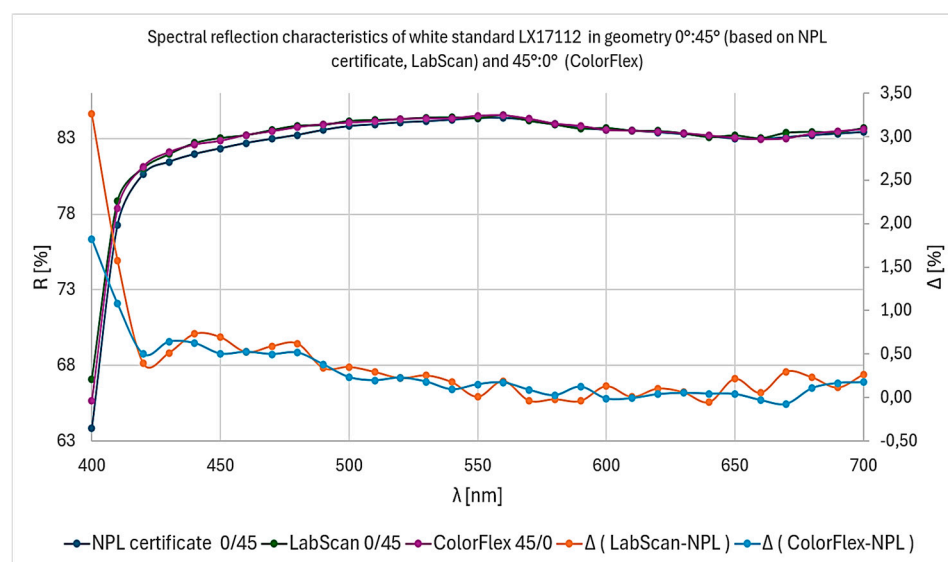


Figure 5. Spectral reflection characteristics of white standard LX17112 in geometry $0^\circ:45^\circ$ (based on an NPL certificate and LabScan) and $45^\circ:0^\circ$ (ColorFlex).

As shown in Figure 5, the characteristics of the spectra obtained during measurements in these two geometries are similar (the differences are of the same order as the measurement uncertainty), which confirms the validity of the Helmholtz rule described

earlier [21–24]. Such small differences between measurements performed on different devices appear to confirm the validity of applying the Helmholtz principle to the measurement geometries of 45°:0° and 0°:45° and the equipment type in question. In our experiments, an attempt was made to test this rule using a device with a different design than the above-mentioned spectrophotometers but enabling the study of the reciprocity phenomenon in any angular configuration.

Using a spectrophotometer with a multi-angle accessory, the spectral reflectance characteristics of eight ceramic standards from the DM05 set, seven Teflon standards, and one enamel standard were determined. The paper presents all of the results of this experiment. In addition, for the purposes of this article, sample representations were additionally extracted, treating their results as a representation for each set of standards, taking into account the type of material from which they are made (ceramic, Teflon, and enamel metal surface).

From this study, spectral reflectance values were obtained for individual standards in the appropriate angular geometry. The result for each setting within a given measurement geometry (reflected light signal) is the average of five repetitions. During all repeated measurements, the samples were kept in a fixed position. The reported spectra represent average measurements. The difference between the reflected light signals for the angular geometry and its inverse was calculated. To eliminate the effects of variations in spectral characteristics (and corresponding signals), these signals were normalized, i.e., each difference in signal at a given wavelength was divided by the signal obtained at the angular geometry x:0 for that wavelength:

$$\delta_w = (S_{x:0} - S_{0:x}) / (S_{x:0}) = \Delta / (S_{x:0}) \quad (1)$$

where

δ_w —relative deviation (differences between nominally reciprocal configurations, relative to the reflection signal in the x:0 geometry) in %;

$\Delta = (S_{x:0} - S_{0:x})$ —difference between the signals measured at the same wavelength in the two inverse geometries;

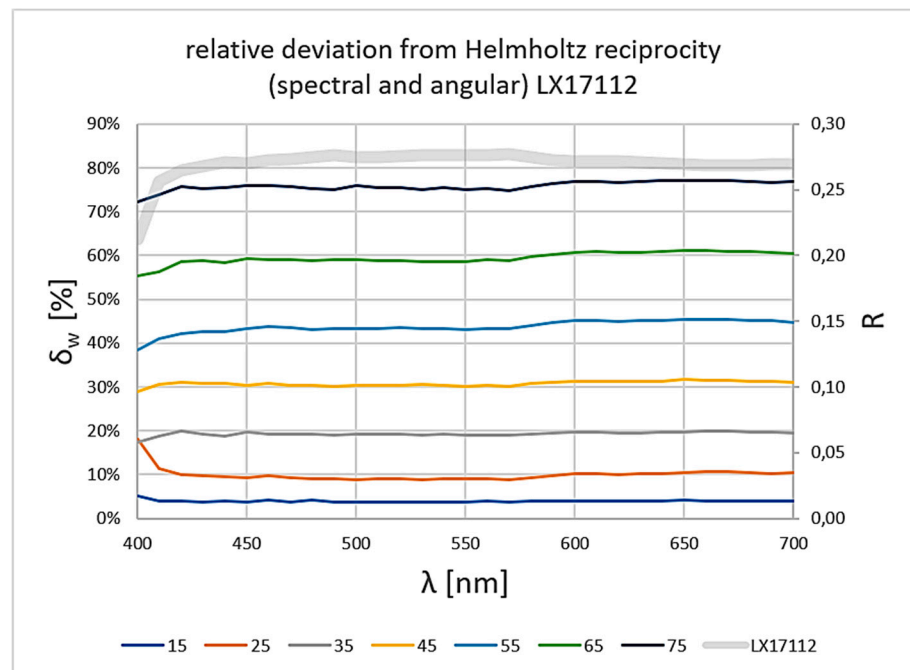
$S_{x:0}$ —signal in the x:0 measurement geometry, the beam incident at a selected angle (x degrees), and the reflected signal measured for 0 degrees;

$S_{0:x}$ —signal in the 0:x measurement geometry, the beam incident perpendicularly to the sample (angle 0 degrees), and the reflected signal measured for an angle of x degrees.

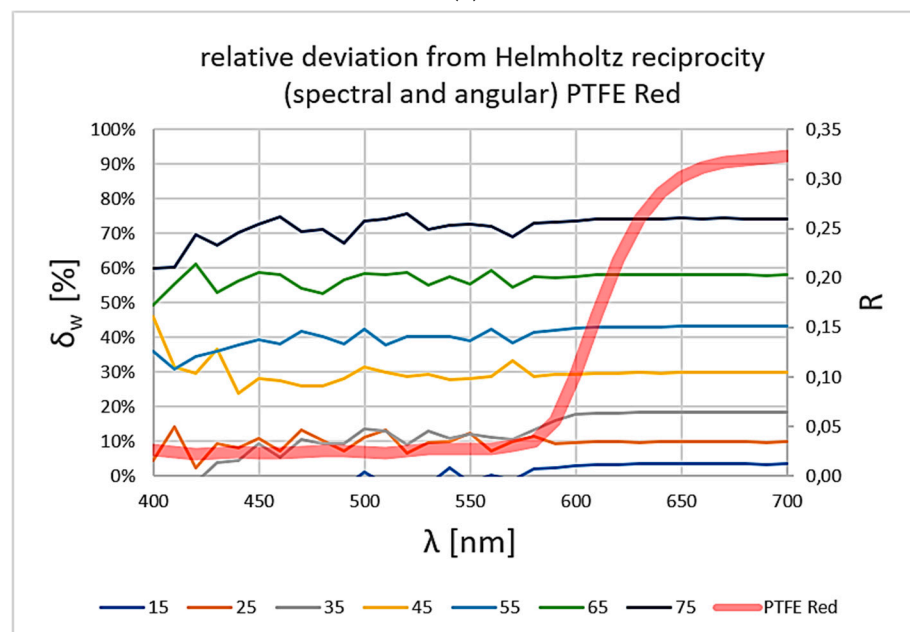
Computational analysis was performed for measurements in the wavelength range of 400 nm to 700 nm. Based on this, an attempt was made to estimate the deviations from the Helmholtz reciprocity principle for inverse geometries across the entire accessible hemisphere (all angles are shown in Figure 5).

As shown in Figure 6a–c, the ordinate axis shows the deviation from the Helmholtz reciprocity principle, while the abscissa axis indicates the wavelength range. The colored curves on the graph correspond to the angular orientation of the sample. Additionally, using the secondary axis and bold lines, Figure 6a–c show the spectral distributions of the corresponding color standards (the absolute signal reflected from the sample measured by the detector in the 15°:0° geometry). Based on these graphs, we can conclude that with increasing observation angles, the deviation from the Helmholtz reciprocity principle increases linearly, which can be associated with a growing contribution of scattered light at large incidence or reflection angles. The examples show that the deviations for each angular setting are constant and do not change with wavelength (despite the use of samples with a reflection characteristic strongly dependent on wavelength). In low-level reflection zones, the calculated deviations lose their constant value due to the greater influence of the noise-to-signal ratio when recording small signals in both geometries. Another observation is that we obtain similar constancy of such deviation distributions not only regard-

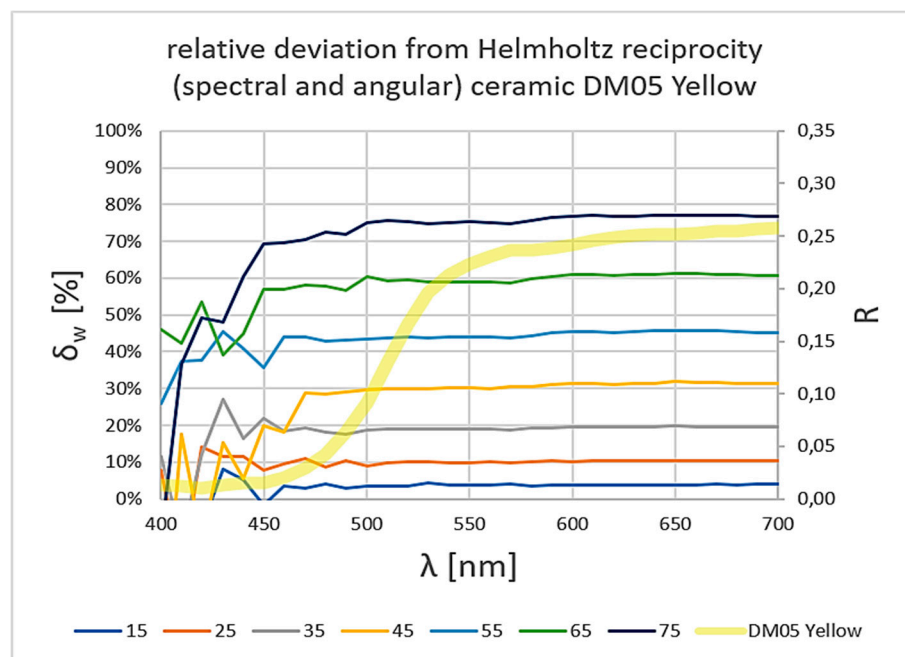
less of the color type of the given standard (in zones of strong signal), but also regardless of the type of material from which the standard is made (glossy ceramic, matte Teflon, or glossy enamel).



(a)



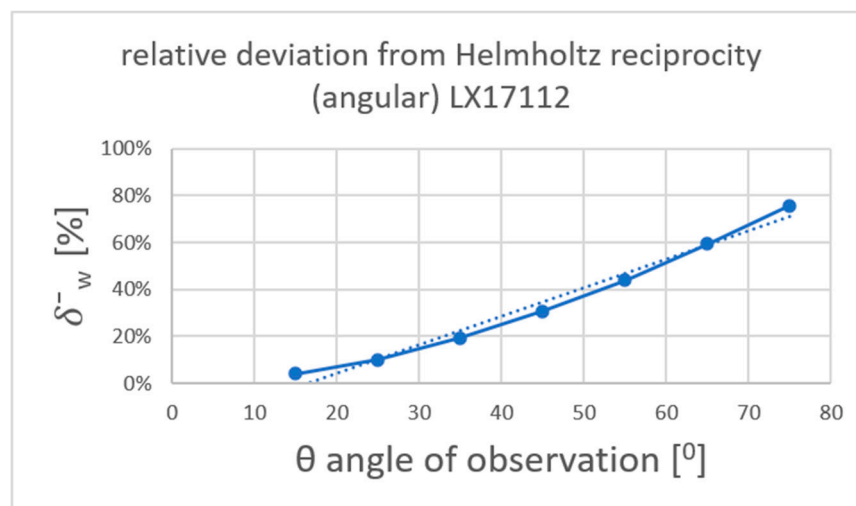
(b)



(c)

Figure 6. Distributions of deviations from the Helmholtz reciprocity principle depending on the angular orientation of the sample. (a) For the white enamel reference standard LX17112. (b) For the red Teflon PTFE standard. (c) For the yellow ceramic DM05 standard.

In the next step of examining deviations from the Helmholtz reciprocity principle in the experiments conducted here, the dependence of spectrally averaged deviations on the applied receiver angular settings (observation angle) was analyzed. The obtained dependencies are presented in Figure 7a–c.



(a)

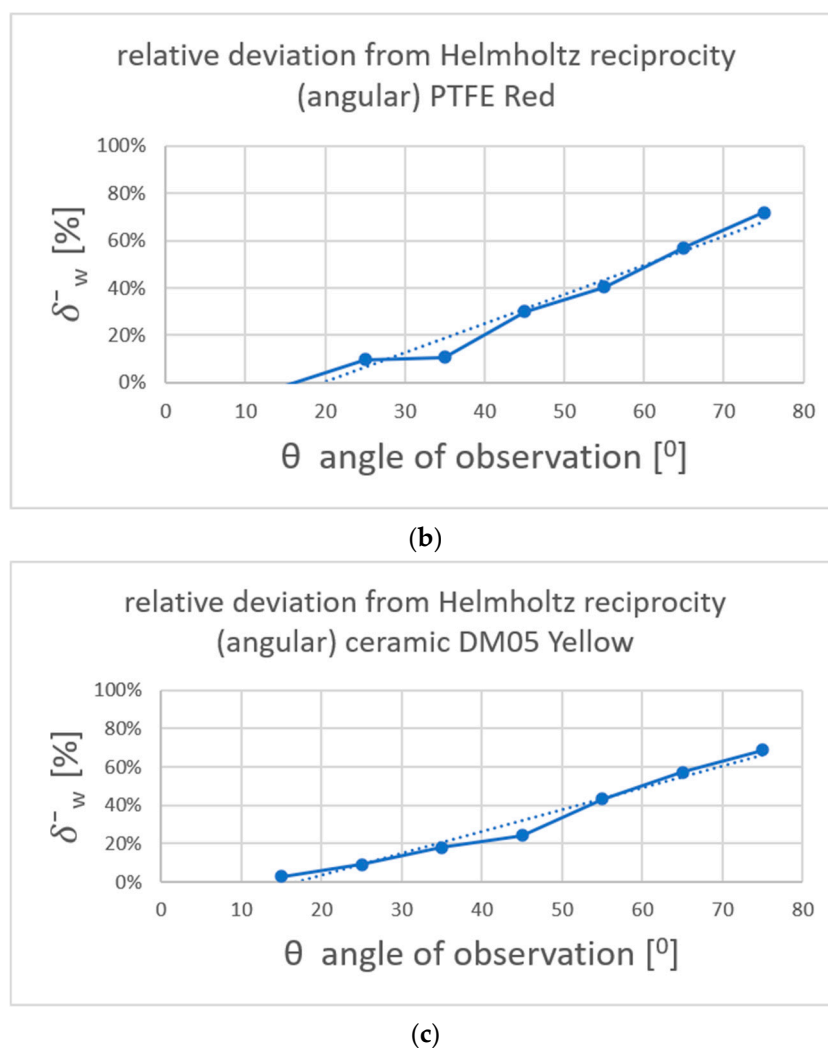


Figure 7. Angular variation in deviations from the Helmholtz reciprocity principle depending on the angular orientation of the detector. (a) For the white enamel reference standard LX17112. (b) For the red PTFE Teflon standard. (c) For the yellow DM05 ceramic standard.

With increasing observation angles, the deviation from the Helmholtz reciprocity principle increases almost linearly; it is the lowest for the angle of 15 degrees and highest for the sample measured at an angle of 75 degrees. As was the case with the spectral data analysis, this phenomenon appears to be constant, independent of the color characteristics and material type. This can be preliminarily explained by the applied measurement geometry, which is fundamentally influenced by the detector's fixed field of view (three angular degrees), while the shape of the light spot on the sample changes with the angle. For smaller angles, higher light signals occur from the more focused spots; for larger angles, this proportion may change with increasing light scattering on the sample.

Observing the similar behavior of the samples, regardless of the material type or color of the reference, the results from all 16 samples tested were averaged (simple arithmetic mean) for specific angular settings ranging from 15° to 75° in 10° increments. The obtained relationships are presented in the graphs (Figures 8 and 9).

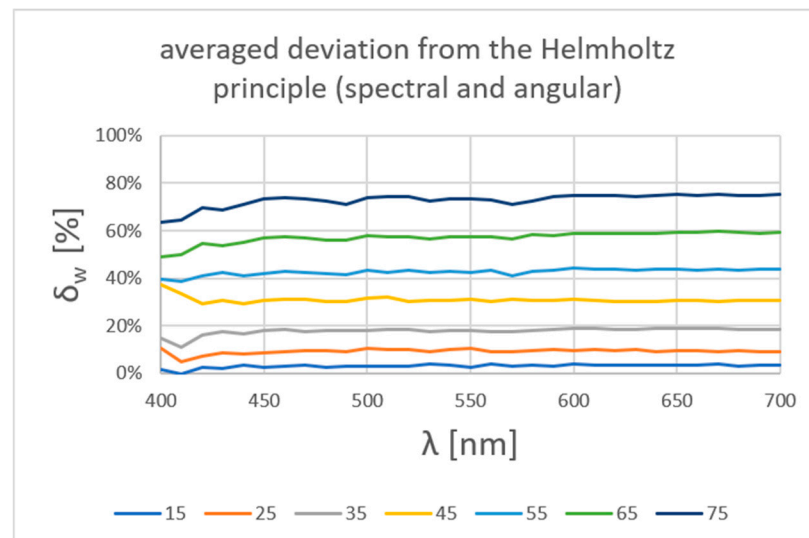


Figure 8. Spectral distributions of deviations from the Helmholtz reciprocity principle obtained from the averages of all 16 examined samples as a function of the sample's observation angle.

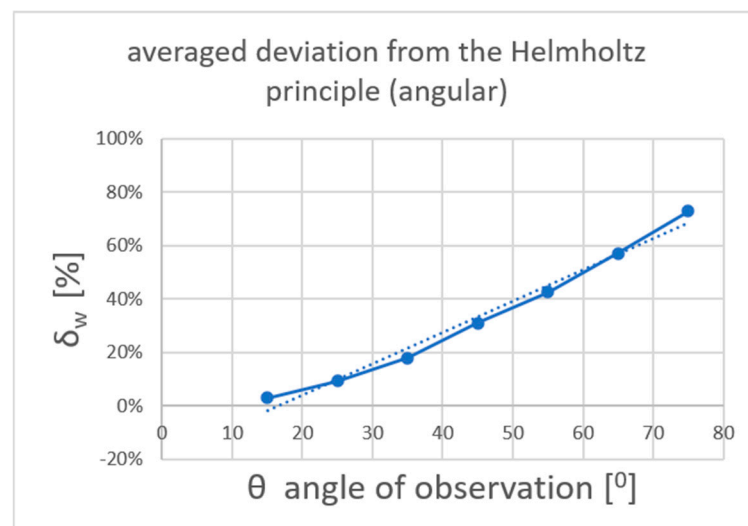


Figure 9. Deviations from the Helmholtz reciprocity principle obtained from the averages of all 16 samples examined as a function of the sample's observation angle.

The results presented here are based on measurements taken from the 'right side' of the hemisphere (as illustrated in Figure 5), but control checks using data from the 'left side' of the hemisphere confirmed the same character of the spectral and angular dependencies observed here.

4. Conclusions

The study aimed to observe the potential variability of the reflection characteristics of various types of standards, assuming the principle of reversibility of measurement geometries (Helmholtz), and to analyze potential deviations from this principle, in close connection with the capabilities and limitations of the measurement system used. For all the tested standards—ceramic, Teflon, and an enameled reference standard—similar trends in the reflected signal were obtained, regardless of the material type, gloss level, or color of the sample.

The relative deviations (differences between nominally reciprocal configurations) between the inverse measurement geometries increase linearly with increasing observation angle, which can be associated with a growing contribution of scattered light at large in-

cidence or reflection angles. Despite the growth of these deviations, their profiles remain stable within the visible range, and the characteristics remain repeatable at a given wavelength.

An analysis of the averaged results for all standards showed that the dependence of the deviations on the angle is systematic, indicating the possibility of modeling and predicting the behavior of the measurement system.

The obtained results confirm that the spectrophotometer equipped with an angular measurement accessory enables reliable examination of the applicability of the Helmholtz reciprocity principle in arbitrary angular configurations, and that its use can broaden the scope of analyses of the reflective properties of colorimetric standards.

The unexpectedly large discrepancy between measurements in the 45:0 and 0:45 configurations, compared with the results obtained using spectrophotometers dedicated to these geometries (as presented in the introduction), most likely arises from structural limitations of the applied setup and from the inability to fully preserve geometric equivalence when interchanging the directions of illumination and observation (detection).

The results provide a basis for further work assessing the stability of reflective standards and improving calibration procedures in directional geometries. Based on the obtained findings and the conclusions drawn from them, further efforts will be undertaken to optimize the measurement conditions in order to gain additional insight into the applicability of the Helmholtz reciprocity principle across various angular configurations using the multi-angle accessory at the Central Office of Measures. While simultaneously acknowledging the need for further analysis of the results, the next stage should include an attempt to combine the obtained outcomes with the associated measurement uncertainty.

Author Contributions: Conceptualization, M.S., Ł.L., M.Z. and K.H.; Methodology, M.S., Ł.L., M.Z., S.G. and K.H.; Software, M.S. and Ł.L.; Validation, M.S., Ł.L. and S.G.; Formal analysis, M.S., Ł.L., M.Z. and S.G.; Investigation, M.S., Ł.L. and M.Z.; Resources, M.S., M.Z. and S.G.; Data curation, M.S.; Writing—original draft, M.S., Ł.L. and S.G.; Writing—review & editing, M.S., Ł.L. and M.Z.; Visualization, M.S., Ł.L. and S.G.; Supervision, M.S., Ł.L., M.Z. and S.G.; Project administration, M.S.; Funding acquisition, M.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research and APC was funded by the minister responsible for science under contract No. DWD/6/0433/2022.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: The research was carried out as part of the implementation doctorate (sixth edition) carried out at the Białystok University of Technology and as a part of work WZ/WE-IA/3/2023. This research and APC was funded by the minister responsible for science under contract No. DWD/6/0433/2022.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Skrzetuszewski, M.; Zajkowski, M.; Górnik, S. Przegląd metodologii związanej z wielokątowym charakteryzowaniem wzorców widmowego współczynnika odbicia. *Przegląd Elektrotech.* **2024**, *3*, 259–263.
2. Beretta, G.B. Spectrophotometer Calibration and Certification. In *HPL-1999-2*; HP Laboratories Palo Alto: Palo Alto, CA, USA, 1999. Available online: https://www.researchgate.net/publication/237328475_Spectrophotometer_Calibration_and_Certification (accessed on 1 April 2026).
3. Żagan, W. *Podstawy Techniki Świetlnej*, 3rd ed.; Oficyna Wydawnicza Politechniki Warszawskiej: Warszawa, Poland, 2022.

4. Mielicki, J. *Zarys Wiadomości O Barwie*; Fundacja Rozwoju Polskiej Kolorystyki: Łódź, Poland, 1997.
5. Korifi, R.; Le Dréau, Y.; Antinelli, J.F.; Valls, R.; Dupuy, N. CIEL*a*b* color space predictive models for colorimetry devices—Analysis of perfume quality. *Talanta* **2013**, *104C*, 58–66. <https://doi.org/10.1016/j.talanta.2012.11.026>.
6. Cinko, U.O.; Becerir, B. Computing characteristics of color difference formulas for regular coordinate changes in CIELAB color space. *Text. Res. J.* **2024**, *95*, 1387–1408. <https://doi.org/10.1177/00405175241278025>.
7. Wyszecki, G.; Stiles, W.S. *Concepts and Methods, Quantitative Data and Formulae*, 2nd ed.; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 1982. Available online: <https://www.wiley.com/en-us/Color+Science%3A+Concepts+and+Methods%2C+Quantitative+Data+and+Formulae%2C+2nd+Edition-p-9780471399186> (accessed on 3 April 2025).
8. Brasil, F.M.B.A.X. *Samples Certification in Colorimetry for CIELAB Color Space*; NOVA School of Science and Technology, NOVA University Lisbon: Lisbon, Portugal, 2021. Available online: https://run.unl.pt/bitstream/10362/147474/1/Brasil_2021.pdf (accessed on 3 April 2025).
9. Listowski, M. The Role of Standard and Supplementary Observers in Accurate Illuminance measurements. *Photonics Lett. Pol.* **2024**, *16*, 52–54.
10. CIE. *CIE 015:2018 Colorimetry*, 4th ed.; Commission Internationale de l’Eclairage: Vienna, Austria, 2018.
11. Fairman, H.; Hemmendinger, H. Stability of Ceramic Reflectance Standards Color. *Color Res. Appl.* **1998**, *23*, 408–415. [https://doi.org/10.1002/\(SICI\)1520-6378\(199812\)23:6%3C408::AID-COL9%3E3.0.CO;2-C](https://doi.org/10.1002/(SICI)1520-6378(199812)23:6%3C408::AID-COL9%3E3.0.CO;2-C).
12. Verrill, J.F.; Malkin, F.; Larkin, J.A.; Wardman, R.H. The BCRA-NPL Ceramic Colour Standards series II—Master spectral reflectance and thermochromism data. *J. Soc. Dye. Colour.* **1997**, *113*, 84–94.
13. Murgai, V.; Staci Klein, S.; Arnold, W.; Durell, C.; Bowers, S.; Russell, B.; Butler, J.J.; Xiong, J.J. Low Degradation Spectralon Selection. In Proceedings of the Earth Observing Systems XXV, Online, 24 August–4 September 2020; p. 115010X. <https://doi.org/10.1117/12.2568774>.
14. Bernad, B.; Ferrero, A.; Strothkämper, C.; Campos, J.; Pons, A.; Quast, T.; Hauer, K.-O.; Schirmacher, A. Deviation of white diffuse reflectance standards from perfect reflecting diffuser at visible and near-infrared spectral ranges. *Metrologia* **2019**, *56*, 055005. <https://doi.org/10.1088/1681-7575/ab3351>.
15. Rezazadeh, Y.; Sperling, A.; Gerloff, T.; Krüger, U.; Ferrero, A.; Campos, J.; Pellegrino, O.; Dubard, J.; Ikonen, E. Uncertainty of Evaluation of Spectral Mismatch Correction Factor. *J. Phys. Conf. Ser.* **2024**, *2864*, 012019. <https://doi.org/10.1088/1742-6596/2864/1/012019>.
16. Skrzetuszewski, M.; Zajkowski, M.; Górnik, S.; Hovorova, K. Testing the spectral characteristics of reflective materials using a multi-angle attachment. In *Science and Industry—Challenges and Opportunities*; Wydawnictwo UMCS: Lublin, Poland, 2024; pp. 256–259. Available online: https://wydawnictwo.umcs.eu/js/elfinder/files/Ebook/SICO_2024.pdf (accessed on 1 April 2025).
17. Skrzetuszewski, M.; Litwiniuk, Ł.; Zajkowski, M.; Górnik, S. Analysis of Color Fade Phenomenon in Studies on the Multi-Angle Characterization of Spectral Reflectance Standards. *Photonics* **2025**, *12*, 915. <https://doi.org/10.3390/photonics12090915>.
18. Nakamura, S.; Inoue, S.; Igarashi, Y.; Sato, H.; Mizokami, Y. Analysis of Gloss Unevenness and Bidirectional Reflectance Distribution Function in Specular Reflection. *J. Imaging* **2024**, *10*, 146. <https://doi.org/10.3390/jimaging10060146>.
19. Nicodemus, F.E.; Richmond, J.C.; Hsia, J.J.; Ginsberg, I.; Limperis, T. Geometrical Considerations and Nomenclature for reflectance. *Natl. Bur. Stand. Monogr.* **1977**, *4*, 160. <https://doi.org/10.6028/NBS.MONO.160>.
20. Hapke, B. A miscellany of bidirectional reflectances and related quantities. In *Theory of Reflectance and Emittance Spectroscopy*; Cambridge University Press: Cambridge, UK, 2012; pp. 263–286. <https://doi.org/10.1017/CBO9781139025683>.
21. Potton, R.J. Reciprocity in Optics. *Rep. Prog. Phys.* **2004**, *67*, 717–754. <https://doi.org/10.1088/0034-4885/67/5/R03>.
22. Shelankov, A.L.; Pikus, G.E. Reciprocity in Reflection and Transmission of Light. *Phys. Rev. B* **1992**, *46*, 3326. <https://doi.org/10.1103/PhysRevB.46.3326>.
23. Zickler, T.E.; Belhumeur, P.N.; Kriegman, D.J. Helmholtz Stereopsis: Exploiting Reciprocity for Surface Reconstruction. *Int. J. Comput. Vis.* **2002**, *49*, 215–227. <https://doi.org/10.1023/A:1020149707513>.
24. Guo, C.; Fan, S. Reciprocity Constraints on Reflection. *Phys. Rev. Lett.* **2022**, *128*, 256101. <https://doi.org/10.1103/PhysRevLett.128.256101>.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.