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COMMISSION INTERNATIONALE DE L'ECLAIRAGE
INTERNATIONAL COMMISSION ON ILLUMINATION
INTERNATIONALE BELEUCHTUNGSKOMMISSION

**Proceedings of the
CIE Expert Symposium on
Spectral and Imaging Methods
for Photometry and Radiometry**

30-31 August 2010

Bern, Switzerland

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THE INTERNATIONAL COMMISSION ON ILLUMINATION

The International Commission on Illumination (CIE) is an organisation devoted to international co-operation and exchange of information among its member countries on all matters relating to the art and science of lighting. Its membership consists of the National Committees in about 40 countries.

The objectives of the CIE are:

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3. To provide guidance in the application of principles and procedures in the development of international and national standards in the fields of light and lighting.
4. To prepare and publish standards, reports and other publications concerned with all matters relating to the science, technology and art in the fields of light and lighting.
5. To maintain liaison and technical interaction with other international organisations concerned with matters related to the science, technology, standardisation and art in the fields of light and lighting.

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LA COMMISSION INTERNATIONALE DE L'ECLAIRAGE

La Commission Internationale de l'Eclairage (CIE) est une organisation qui se donne pour but la coopération internationale et l'échange d'informations entre les Pays membres sur toutes les questions relatives à l'art et à la science de l'éclairage. Elle est composée de Comités Nationaux représentant environ 40 pays.

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1. De constituer un centre d'étude international pour toute matière relevant de la science, de la technologie et de l'art de la lumière et de l'éclairage et pour l'échange entre pays d'informations dans ces domaines.
2. D'élaborer des normes et des méthodes de base pour la métrologie dans les domaines de la lumière et de l'éclairage.
3. De donner des directives pour l'application des principes et des méthodes d'élaboration de normes internationales et nationales dans les domaines de la lumière et de l'éclairage.
4. De préparer et publier des normes, rapports et autres textes, concernant toutes matières relatives à la science, la technologie et l'art dans les domaines de la lumière et de l'éclairage.
5. De maintenir une liaison et une collaboration technique avec les autres organisations internationales concernées par des sujets relatifs à la science, la technologie, la normalisation et l'art dans les domaines de la lumière et de l'éclairage.

Les travaux de la CIE sont effectués par 7 Divisions, ayant chacune environ 20 Comités Techniques. Les sujets d'études s'étendent des questions fondamentales, à tous les types d'applications de l'éclairage. Les normes et les rapports techniques élaborés par ces Divisions Internationales de la CIE sont reconnus dans le monde entier.

Tous les quatre ans, une Session plénière passe en revue le travail des Divisions et des Comités Techniques, en fait rapport et établit les projets de travaux pour l'avenir. La CIE est reconnue comme la plus haute autorité en ce qui concerne tous les aspects de la lumière et de l'éclairage. Elle occupe comme telle une position importante parmi les organisations internationales.

DIE INTERNATIONALE BELEUCHTUNGSKOMMISSION

Die Internationale Beleuchtungskommission (CIE) ist eine Organisation, die sich der internationalen Zusammenarbeit und dem Austausch von Informationen zwischen ihren Mitgliedsländern bezüglich der Kunst und Wissenschaft der Lichttechnik widmet. Die Mitgliedschaft besteht aus den Nationalen Komitees in rund 40 Ländern.

Die Ziele der CIE sind:

1. Ein internationaler Mittelpunkt für Diskussionen aller Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik und für den Informationsaustausch auf diesen Gebieten zwischen den einzelnen Ländern zu sein.
2. Grundnormen und Verfahren der Meßtechnik auf dem Gebiet der Lichttechnik zu entwickeln.
3. Richtlinien für die Anwendung von Prinzipien und Vorgängen in der Entwicklung internationaler und nationaler Normen auf dem Gebiet der Lichttechnik zu erstellen.
4. Normen, Berichte und andere Publikationen zu erstellen und zu veröffentlichen, die alle Fragen auf dem Gebiet der Wissenschaft, Technik und Kunst der Lichttechnik betreffen.
5. Liaison und technische Zusammenarbeit mit anderen internationalen Organisationen zu unterhalten, die mit Fragen der Wissenschaft, Technik, Normung und Kunst auf dem Gebiet der Lichttechnik zu tun haben.

Die Arbeit der CIE wird in 7 Divisionen, jede mit etwa 20 Technischen Komitees, geleistet. Diese Arbeit betrifft Gebiete mit grundlegendem Inhalt bis zu allen Arten der Lichtanwendung. Die Normen und Technischen Berichte, die von diesen international zusammengesetzten Divisionen ausgearbeitet werden, sind von der ganzen Welt anerkannt.

Alle vier Jahre findet eine Session statt, in der die Arbeiten der Divisionen überprüft, berichtet und neue Pläne für die Zukunft ausgearbeitet werden. Die CIE wird als höchste Autorität für alle Aspekte des Lichtes und der Beleuchtung angesehen. Auf diese Weise unterhält sie eine bedeutende Stellung unter den internationalen Organisationen.

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INTRODUCTION

This Symposium was organised by CIE Division 2 in cooperation with the Swiss Lighting Society (SLG), and was hosted by the Federal Office of Metrology (METAS), Bern, Switzerland. The two-day Symposium included a one day tutorial presenting the state-of-the-art techniques in the field of photometry. Invited experts provided eight lectures from basic concepts to advanced techniques in photometric and colorimetric measurements, aiming at optical measurement engineers in a wide range of fields including LED and solid state lighting. On the second day, a Scientific Symposium featured 35 contributed papers presenting recent research in photometry, colorimetry, and radiometry with a focus on the methods using spectral and imaging techniques.

The Symposium had four sessions, Session I: Goniophotometry and Spatial Methods, Session II: Imaging and Spectral Methods, Session III: Metrology for LEDs, and Session IV: Advances in Radiometry, with 16 oral presentations and 19 poster presentations.

The Symposium was followed by CIE Division 2 Technical Committee meetings and annual Division meeting for three days.



Expert Symposium on Spectral and Imaging Methods for Photometry and Radiometry

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SPECTRAL RAY TRACING FROM NEAR FIELD GONIOPHOTOMETER MEASUREMENTS

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Radiant Imaging, Inc., USA

ABSTRACT

Measured light source models have been widely used in ray trace simulations for optical design for more than 15 years now, but to date the generated ray sets have not contained spectral information. In some limited cases, tristimulus measurements can be helpful, but most ray tracing software requires a specific wavelength assigned to each ray to enable full color simulations of an optical system.

This paper describes and tests various techniques for combining spectral measurements with either photopic or tristimulus imaging colorimeters to produce ray sets that contain a wavelength. These ray sets can generally be readily used by most ray-tracing software to more accurately refract and diffract rays through the optical system and to generate illuminance or luminance distributions that also include colorimetric information.

Finally the methods are tested with real light sources where spectral power distribution varies significantly spatially across the light source and/or as a function of angle.

Keywords: near field, goniophotometry, spectral measurement, white LED, source model, source imaging goniometer.

1. INTRODUCTION (Source Models from photopic to spectral)

Near field goniophotometry has been successfully used to create source models of light sources used in optical ray tracing simulations for over 15 years [1,2,3] and to also enable measurements of luminaires in the near field which can then be used to determine illuminance distributions at any distance or to calculate far-field luminous intensity.

Initially these near-field measurements were done with only photopic filters, which was adequate for tungsten lamps that

exhibited minimal color variation across the light emitting regions of the light source. As metal halide sources and more recently white LEDs became more commonly used in illumination applications, measuring the color variation across the light source has become increasingly important as this variation can migrate into unwanted color variation in the output of the optical system, whether it be a projector, automotive headlamp, or a luminaire.

Subsequent addition of tristimulus filters has enabled some basic color analysis to be performed. However most optical design ray tracing tools cannot accept and trace rays based on tristimulus data. Instead ray tracing software generally has the ability to trace a ray with an assigned specific wavelength because a specific wavelength for each ray is necessary to determine how the ray refracts, diffracts or interferes through glass or thin film coatings.

This paper describes a technique to combine spectral measurements with near field goniometric measurements to enable generation of rays with an assigned specific wavelength.

2. METHODS FOR INCLUDING SPECTRAL DATA

Generally if the spectrum of a light-emitting device is known and many rays, typically on the order of millions, are generated, then wavelengths can be assigned to those rays by use of importance sampling. With importance sampling, wavelengths that have a higher relative power will have relatively more rays assigned with that wavelength. For example if a light source has a spectral power distribution function where there is two times the power generated at 655 nm vs. 450nm, then twice as many rays in the ray set will be assigned a wavelength of 655 nm vs. 450 nm. See Figure 1 below.

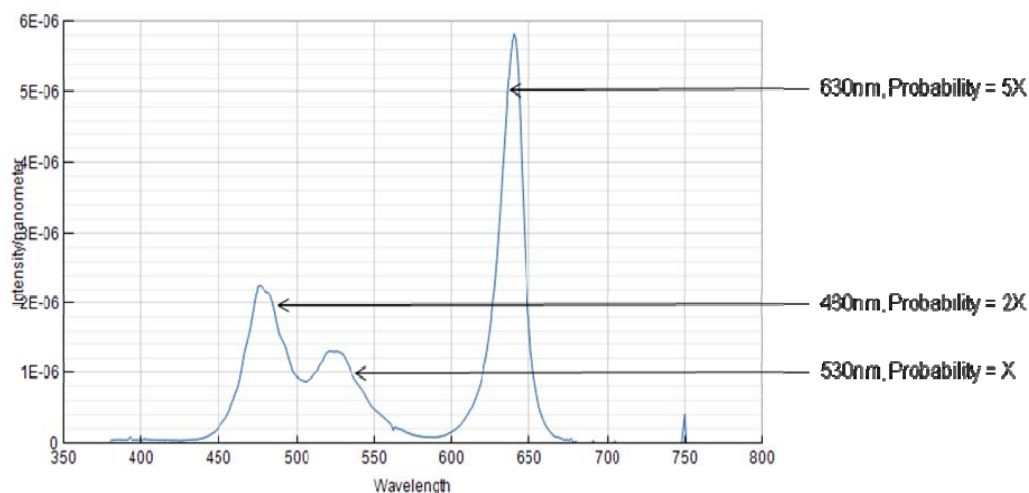


Figure 1. Selecting a wavelength using Importance Sampling.

In the ideal case, a hyper spectral imaging device would be used to measure the spectral power distribution from all angles with good spatial resolution. In that case it would be straightforward to assign each ray with a wavelength based on the emitting location and view angle, and by using the importance sampling technique described above. But there are several drawbacks for using a hyperspectral imaging system. One is that photopic only or tristimulus measurements already are quite large, typically requiring hundreds of megabytes of storage space, and a hyperspectral measurement would likely make the size at least an order of magnitude larger. Secondly these source models typically include more than 1,000 individual imaging colorimeter measurements [4] and hyperspectral imaging system measurements take much more time than a photopic or tristimulus measurement. This would mean a 4π measurement could take 20 hours or more vs. 1-2 hours for a tristimulus measurement.

There are several alternatives to assigning wavelengths to rays using a combination of photopic or tristimulus measurements and knowledge of or measurement of the spectral power distribution, and these methods are the core topic of this paper. Four such methods are described below.

1. The known source spectrum as measured by an integrating sphere can be imported into the ray generation software, and each ray may be assigned a wavelength based on the relative spectral power

distribution. This method does at least provide the ray tracing software a wavelength that is quite useful as mentioned above, but if the light source exhibits significant variation in spectrum as a function of angle or spatially, then this method might not be adequate.

2. With the addition of a spectrometer to the source imaging goniometer, the spectrum could be measured at each view angle where a spatial distribution image measurement is made. Then during ray generation, each unique measured spectrum could be used to assign a wavelength depending on the emitted direction of the ray. But if there is significant color variation spatially across the light source, this method might still prove inadequate.
3. If a tristimulus measurement is made at each direction rather than just a photopic measurement, knowledge of the integrated spectrum as in method #1 could be used in combination. First a modified spectrum can be generated based on the known tristimulus data (or color coordinate) for each light-emitting location of each image. Once this modified spectrum is generated, it can then be used in the same way to assign wavelengths based on importance sampling.
4. A combination of measuring the spectrum at every angle and measuring with a tristimulus imaging colorimeter enables an even more accurate technique for assigning

wavelengths. Like in #3 described above, a modified spectrum can be generated based on the original spectrum and the known color coordinate of the specific light emitting region of the light source. But unlike #3 above, the original spectrum used would be the one measured in the same direction as the tristimulus measurement.

The process to generate rays and assigning wavelengths to each ray generated is fairly straightforward for methods 1 and 2 described above. As stated, the rays are simply assigned a wavelength based on the relative power of each wavelength of the measure SPD. However, the process described in methods 3 and 4 above, whereby a spectral measurement is combined with a tristimulus measurement to assign a wavelength to a ray, is significantly more complicated. To further explain this process to generate rays with wavelength, it is broken down into 5 basic steps as follows:

1. **Select an initial Spectral Power Distribution (SPD).** This SPD could be measured globally such as in an integrating sphere, or could be measured at each angle where near-field luminance measurements were made. It is best to measure the SPD at each angle because it will require less modification (as described in step 4). See Figure 2 and 3 below.
2. **Select an emission location on the light source.** Generally done via importance sampling based on the luminance distribution.
3. **Determine the color coordinate at emission point.** The spatial measurements must be calibrated colorimetric measurements such that once an emission location is chosen in step 2 above, the chromaticity coordinates will be known.
4. **Adjust the SPD to Match the Color Coordinate.** If there is any color variation across the light source, the chromaticity coordinates of the integrated SPD for a given angle or globally will likely not match the measured chromaticity coordinate of the emission point. We make the assumption that the chromaticity coordinate as measured by the Imaging Colorimeter is correct, and so the SPD must be modified in such a way as to match the known chromaticity coordinate.
5. **Select A Wavelength From The Adjusted SPD.** Based on modified SPD a wavelength can be chosen using importance sampling techniques (see figure 1 above.

There are an infinite number of solutions to generate a SPD that correlates to a target chromaticity coordinate, so the problem of modifying a known SPD to match a target chromaticity coordinate is extremely under constrained. There are many possibilities for performing this modification. The goal is to retain as much of the features of the original SPD as possible when performing the conversion. The technique used in the experiments below used an iterative approach that generally resulted in realizing the target chromaticity coordinate in 1 to 4 iterations. A tolerance or DUV of .003 was chosen, so once a SPD was found that yielded a chromaticity coordinate with the chosen DUV, iterations were stopped. See Figure 4 and 5 below.

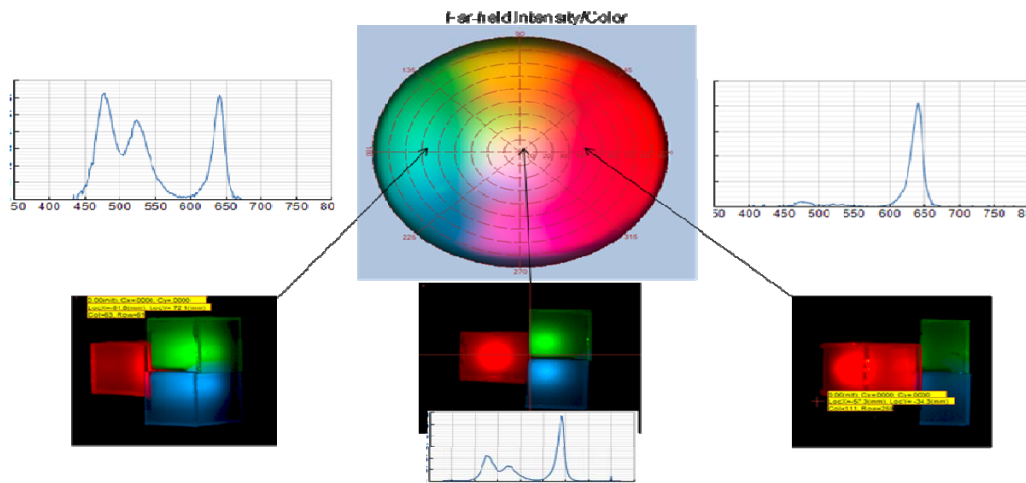


Figure 2. Select an initial spectrum based on the measured spectrum at each view angle.

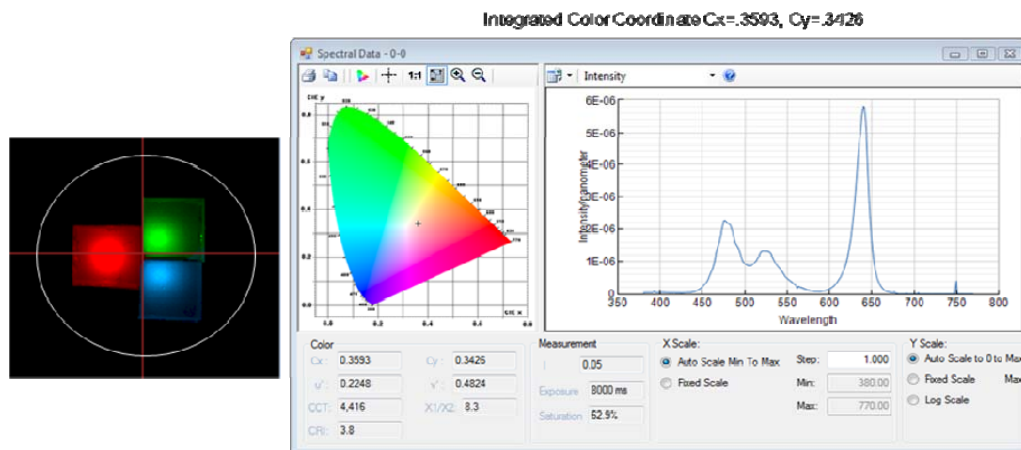


Figure 3. The initial integrated SPD for the chosen image.

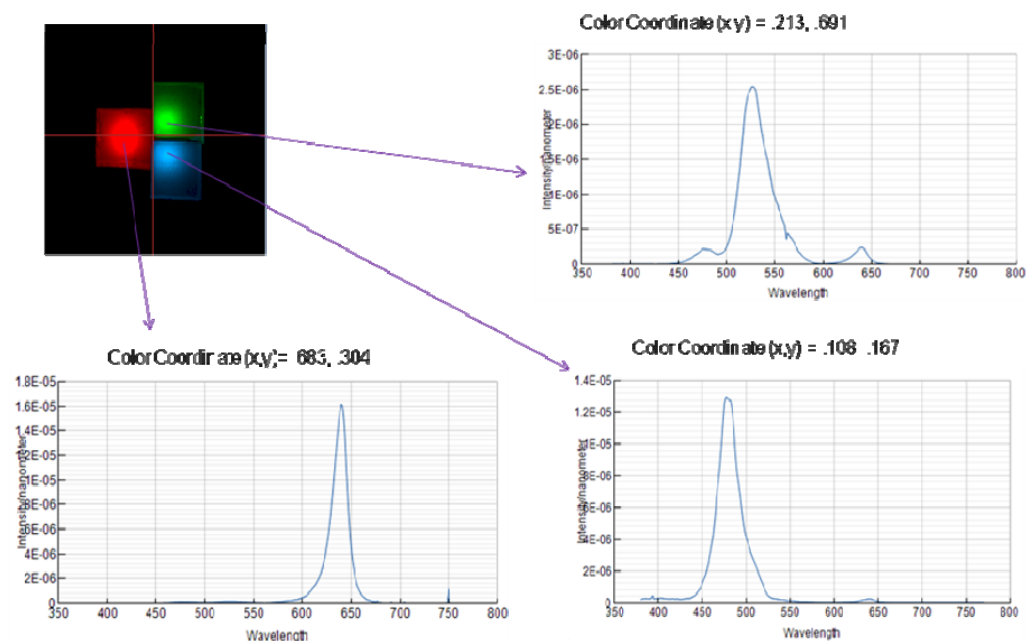


Figure 4. Modify the initial SPD based on known chromaticity coordinate.(RGB light source).

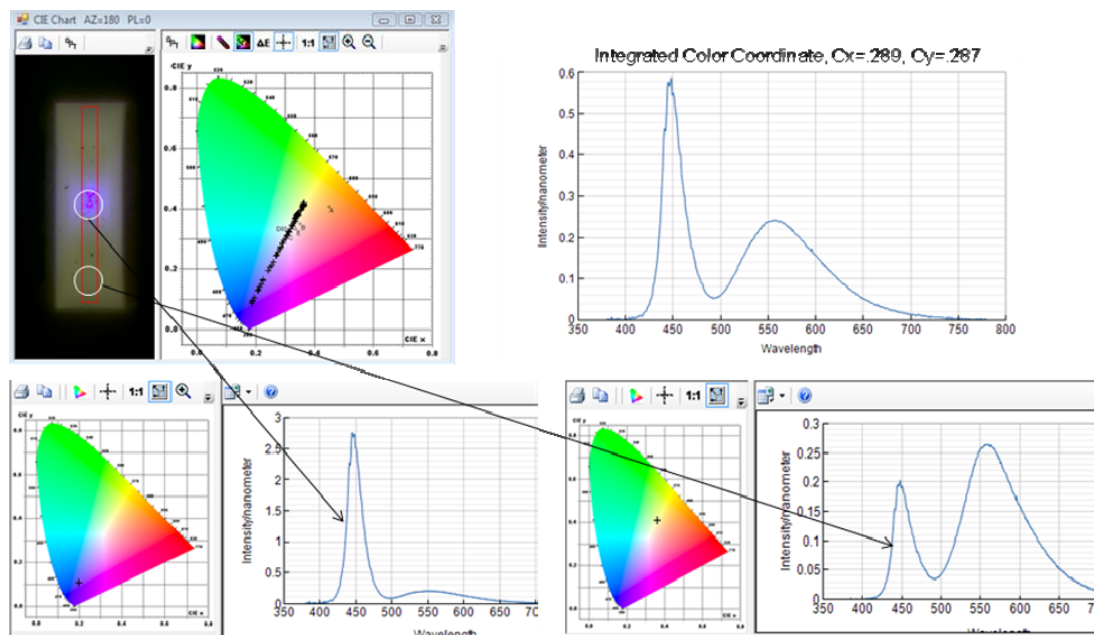


Figure 5. Modify the initial SPD based on known chromaticity coordinate. (White LED).

3. EXPERIMENTAL TESTS

Different light sources including a white LED, a tri-color LED, and a RGB luminaire were measured using the technique described above and then analyzed in ray-tracing software to show the results. For the

experimental tests, two types of near-field imaging goniometers were used. The machine on the left is designed to measure small light sources such as individual LEDs, or LED dies. The machine on the right is used for measuring larger light sources or entire luminaire assemblies.



Figure 6. Imaging Goniometers used in the experiments.

Experiment 1 – Compare global SPD method to SPD measured at each view angle

The first experiment was to compare a modified SPD based on a globally measured SPD, such as done in an integrating sphere, to a modified SPD that was measured specifically for the view angle of the imaging colorimeter measurement. See Figure 7 below. While the modified spectrum generated from the global SPD does match quite well with the modified SPD generated from the SPD measured at a same angle as

the imaging colorimeter, the latter modified SPD does have a better match, especially in the finer features of the SPD.

Therefore it would be recommended that spectral measurements are taken at each view angle where an imaging colorimeter measurement was recorded. But in the case where it is not possible to do so, maybe due to limitations of the measuring equipment, a globally measured SPD measured separately in an integrating sphere does have considerable value and can be used to generate a reasonably good set of spectral rays.

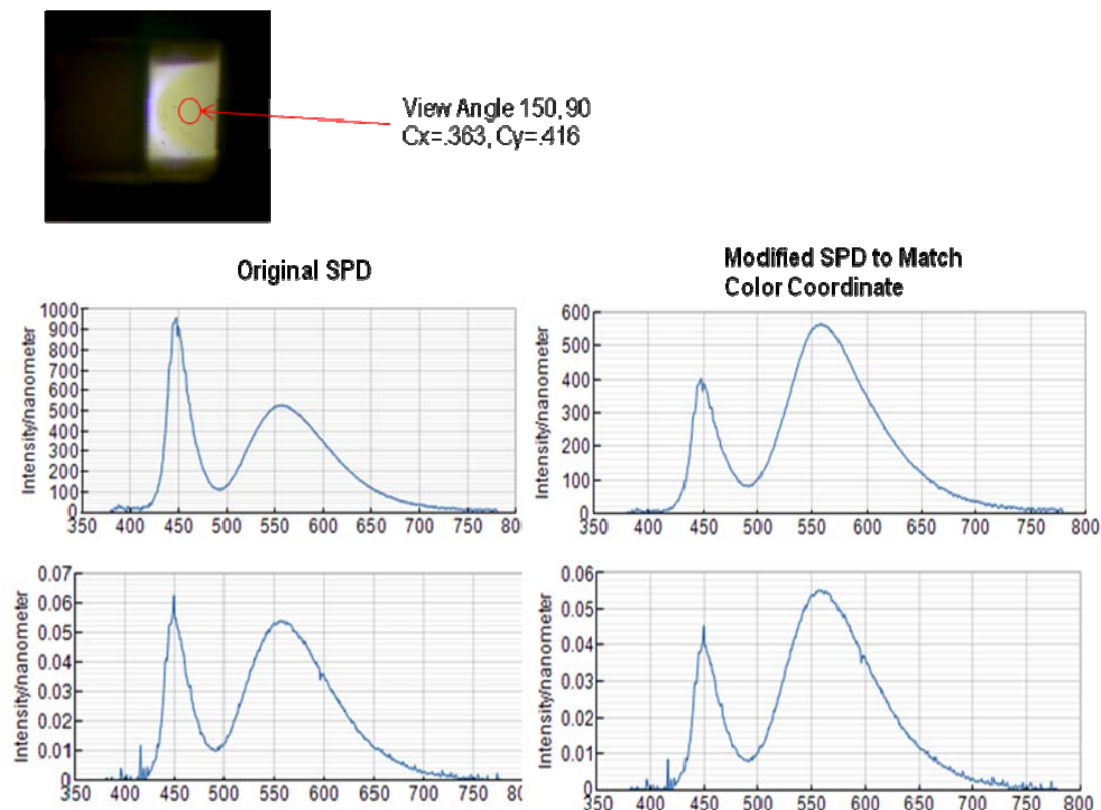


Figure 7. Comparison of modified SPDs created from a global spectrum (top) vs. a SPD measured at the same angle as the imaging colorimeter measurement (bottom)

Experiment 2 – Compare Global SPD to angle-specific SPD for a tricolor LED

The second experiment was simply a study of how much the SPD might vary as a function of view angle for a tricolor LED. The

results show significant variation of the SPD as a function of view angle. Therefore it would clearly be best to use the angle specific SPD rather than a global SPD. See Figure 8 and 9 below.

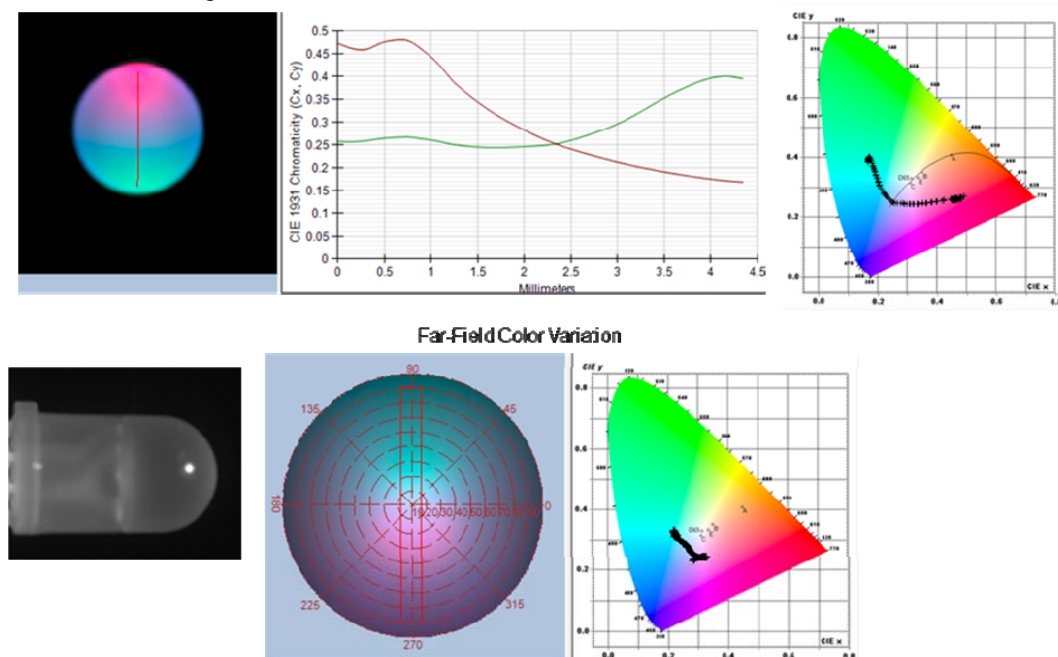


Figure 8. A Tricolor LED.

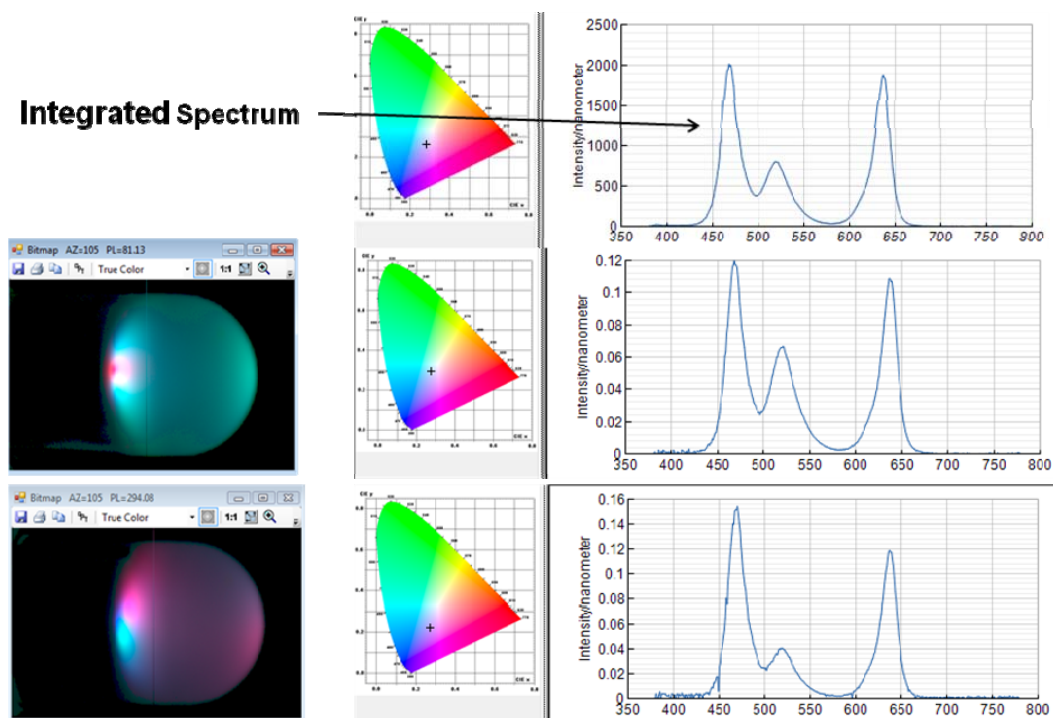


Figure 9. Selected SPDs at various view angles.

Experiment 3 – Ray trace with wavelengths assigned

The third experiment was to perform a ray trace to a plane at 3 distances using the ray

set with spectral data. The results of the ray trace are shown in Figure 10 below.

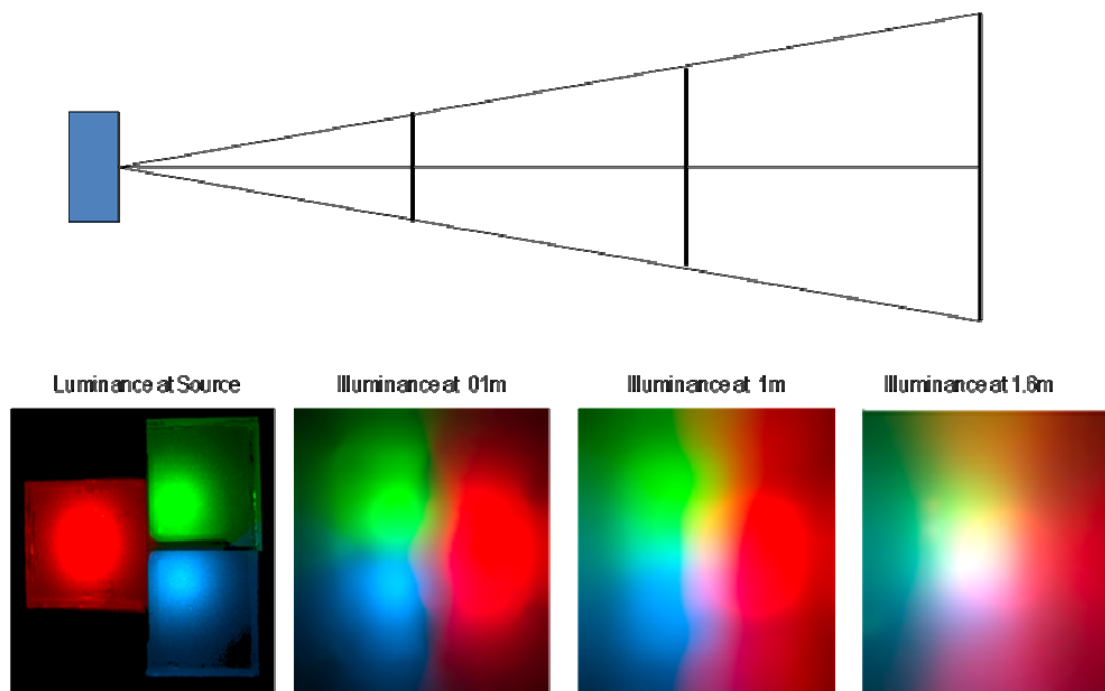


Figure 10. Ray trace a spectral ray set to planes at 3 distances.

4. CONCLUSIONS

The growing use of LEDs and arc lamps in optical and lighting systems has created a need for full color ray trace simulations due to the significant spatial and angular variation in color of the light sources. However, creating near field source models with an imaging colorimeter alone doesn't provide wavelength information, which is generally needed by ray trace simulation software. By combining the imaging colorimeter measurement with a spectral measurement, ray sets can be generated for the ray trace simulation software that have accurate power and wavelength characteristics.

In addition to its utility for optical modeling of light sources, this technique can be applied to complete luminaire assemblies. For full luminaire assemblies, it is very difficult to measure the CRI because a far field measurement of a spatially large luminaire must be performed at a relatively long distance. At such a long distance the signal is likely to be insufficient to perform a direct spectral measurement in the far-field. This technique can be used to make a near field measurement and then perform a spectral ray trace to determine the CRI in the far-field at any angle from the source, using a conveniently small space for the measurement system.

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A COMPARISON BETWEEN NEAR FIELD AND FAR FIELD GONIOPHOTOMETER MEASUREMENTS

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ABSTRACT

Near field goniophotometry is a recent promising measurement technique to determine the photometric characteristics of light sources. At the Light & Lighting Laboratory the recently installed goniophotometers will be used to determine luminous intensity distributions of a wide variety light sources of various dimensions. In this work results obtained with the near field goniophotometer are compared with photometric data obtained with a far field goniophotometer.

The near field goniophotometers allow to obtain information about both the luminous flux and the luminous intensity of light sources. In this paper these parameters were investigated for a calibrated incandescent source and for a remote phosphor LED source.

The luminous flux and luminous intensities as obtained from both lamps are comparable for both near and far field goniophotometers. Small deviations appear during far field goniophotometry due to the lamp motion in this equipment.

Keywords: near field goniophotometer, luminous flux, luminous intensity.

1. INTRODUCTION

Near field goniophotometry is a recent promising measurement technique to determine the photometric characteristics of light sources. This technique makes use of a photometer and an camera with a 2-dimensional CCD array, which are both mounted on the frame of the goniophotometer so that both devices can rotate on a virtual sphere around the light source. The camera is used to measure the relative luminance distribution of the light source from all light emitting directions, while normalization of the data is obtained from the additional luminous flux determination with the photometer. The application of imaging luminance cameras allows for a compact set-up of a near field goniophotometer and consequently smaller room dimensions compared to the conventional far field goniophotometers.

Since a far field goniophotometer experiment yields the luminous intensity data obtained in all light emitting directions, these data can be used to construct the luminous intensity distribution (LID) of the source. In addition, integration of the luminous intensity data yields the luminous flux of the light source. In this paper luminous intensity and luminous flux data obtained from near field goniophotometer measurements at the Light & Lighting Laboratory (Ghent, Belgium) are compared to data obtained from the CIE type II far field goniophotometer at the laboratory.

2. EXPERIMENTAL

2.1 Near field goniophotometers

The new near field goniophotometer at the Light & Lighting Laboratory has been installed in a room acclimatized at 25°C. The camera moves around the geometrical centre located at the intersection of the two rotation axes of the goniophotometer at a distance of 1,50 m. Various optical lenses can be mounted on the camera resulting in a maximum diameter of the luminous area of 2,00 m. The missing solid angle fraction due to the lamp holder for this goniophotometer is only 0,3 %. The CCD camera is equipped with several neutral density filters to increase its dynamic range. Several objectives can be mounted on the camera so that luminaires of a wide range of dimensions can be characterized. The photometer is a 18 bit illuminance meter with 8 measuring ranges, $V(\lambda)$ -calibration ($f_1' < 1,5 \%$) and cosine adaptation. As reference a luminous flux standard incandescent lamp traceable to PTB standards was used.

The far field goniophotometer at the Light & Lighting Laboratory is a CIE type II goniophotometer with a moving source mounted in a rotating frame and a luminance probe as a detector positioned at a distance of 9 m from the light source. The frame limits the maximal dimensions of the sources to 55 cm. Here a spectral irradiance standard incandescent lamp traceable to NPL standards was used.

2.2 Light sources

In order to compare near and far field goniophotometer experiments, stable light sources are required, especially since the far field goniophotometer has a stationary detector while the light source is rotating around two different axes. Two kind of light sources are selected:

- A calibrated incandescent lamp, with traceability to PTB, operated in DC mode at 75 W.
- A remote phosphor high power LED module, operated in AC mode at 47 W.

Since both sources have small dimensions less than 15 cm, the point source approximation is also valid during measurement with the near field goniophotometer. This permits to make a additional comparison with results obtained solely with the photometer of the near field goniophotometer.

3. RESULTS

3.1 Luminous flux measurements

3.1.1 Calibrated incandescent lamp

The luminous flux of the calibrated incandescent lamp has been determined by an accredited third party laboratory as 1334 lm with an uncertainty of $\pm 1,2\%$ ($k = 2$). For luminous flux measurements a complete spherical surface was scanned with steps of 1° for both polar and azimuth angles. The luminous flux Φ can be calculated from the photometer measurements as

$$\Phi = \iint_{\text{sphere}} E \cdot dA$$

From the measurements with the near field goniophotometer values of 1338,2 lm and 1335,1 lm were obtained. These values were obtained with the photometer and differ only by 0,31 % and 0,08 % from the value from the calibration sheet.

Since the far field goniometer allows only measurements in 4 C-planes, the luminous flux of light sources can only be calculated from the radiation pattern in case of light sources having rotational symmetry along the first axis of the luminaire. Although the incandescent lamps are frosted, it will be illustrated in section 3.2 that their radiation pattern is not symmetrical.

3.1.2 Control chart

In the period from May to July 2010 a luminous flux control measurement is performed twice a month in order to track the behaviour of the near field goniophotometer equipment. For this experiment three incandescent lamps are tested and the differences from the luminous flux values as stated in the calibration certificate are reported. The variations in luminous flux are as small as 0,3 % or less, as can be seen in Figure 1. These differences are less than the uncertainty of the calibrated lamps, which means that the goniophotometer equipment has been stable during the testing period.

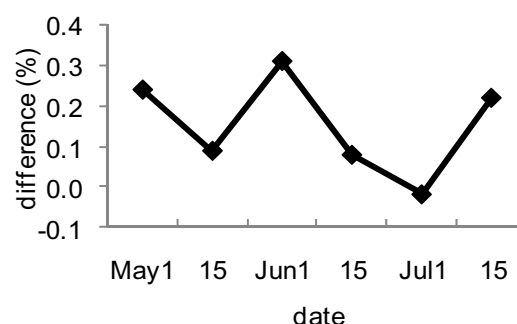


Figure 1. Luminous flux measurement control chart.

3.1.3 LED module

With the photometer of the near field goniophotometer luminous flux values of 1744,3 lm and 1745,2 lm were obtained for the remote phosphor LED module.

Since the radiation pattern of the LED module has rotational symmetry along the first axis of the luminaire, the luminous flux can be calculated from the luminous intensity values as obtained with the far field goniometer. The luminous flux for this LED module is

$$\begin{aligned} \Phi &= \iint_{\vartheta, \phi} I(\vartheta) \cdot d\Omega \\ &= \int d\phi \int I(\vartheta) \cdot \sin \vartheta \cdot d\vartheta \\ &\approx \frac{\pi}{2} \sum_{4\text{Cplanes}} [I(\vartheta) \cdot \sin \vartheta \cdot \Delta \vartheta] \\ &= 1721 \text{ lm} \end{aligned}$$

Considering the expanded uncertainty of 44 lm ($k = 2$) this result corresponds well with the results from the measurements obtained using the near field goniophotometer.

3.2 Luminous intensity measurements

3.2.1 Calibrated incandescent lamp

The luminous intensity values of the incandescent lamp have been determined with the near field goniophotometer both with camera and photometer. The camera with a 25 mm lens (and a field of view of 48 cm x 36 cm at a distance of 1,5 m) took 64358 images of the incandescent lamp as is illustrated in Figure 2, where 4 images in an arbitrary C-plane are shown. From the camera images the relative luminous intensity distribution in any direction can be calculated, while the absolute values are obtained with the help of the integrated photometer readings.

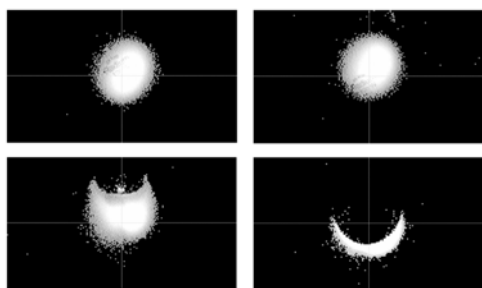


Figure 2. Camera images of the incandescent lamp in one C-plane.

From the luminous intensity distribution a potato shaped radiation pattern was found as shown in the left part of Figure 3. Since this pattern has relatively smooth shape and the small dimensions of 5 cm of the lamp the point source approximation is valid and the luminous intensity values can be calculated from the measured illuminance values as well. In the right part of Figure 3 this pattern is also shown.

The luminous intensity values as obtained with camera and with photometer correspond well. In the normal ($C = 0^\circ, \gamma = 0^\circ$) direction that is located along the first axis of the luminaire and that corresponds to the first photograph of Figure 2, the respective values are 115 cd and 112 cd.

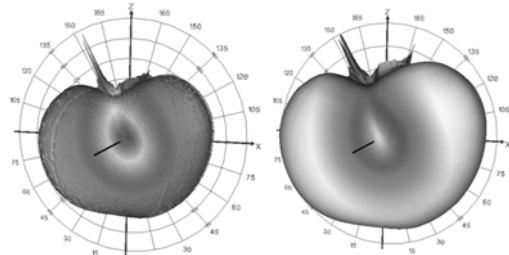


Figure 3. Radiation pattern of an incandescent lamp as registered with

camera (left side) and with photometer (right side).

In order to compare these near field luminous intensity values with the results as obtained with the far field goniophotometer, a far field luminous intensity measurement is made in the horizontal ($\gamma = 90^\circ$) plane perpendicular to the first axis of the lamp. From Figure 4 a good agreement can be observed between both type of measurements in almost all C-planes. Differences are less than 2 %. No correct far field measurements were possible around ($C = 120^\circ$) and ($C = 300^\circ$) planes due to the shadowing effect of the frame with respect to the detector, yielding differences up to 9%.

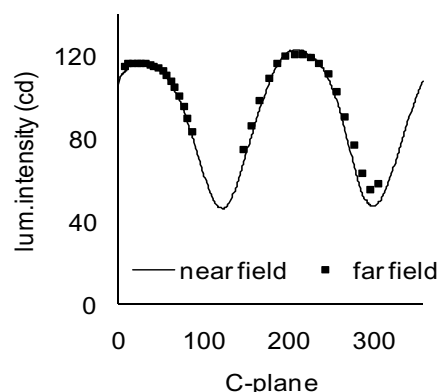


Figure 4. Luminous intensity in the ($\gamma = 90^\circ$) plane of the incandescent lamp obtained from near field (solid line) and far field (dots) measurements.

3.2.2 LED module

Similar tests are also performed on the remote phosphor LED module. The camera images are illustrated in Figure 5, while the radiation pattern as registered by camera and by photometer are shown in Figure 6. From these figures it can be seen that this hemispherical LED module radiates almost like a lambertian source.

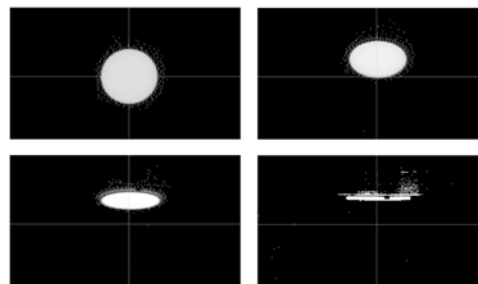


Figure 5. Camera images of the LED module in one C-plane.

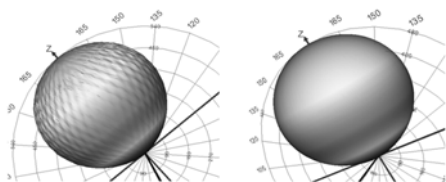


Figure 6. Radiation pattern of a LED module as registered with camera (left side) and with photometer (right side).

However the radiation pattern found with the photometer is somewhat elliptical, since near the equatorial plane ($\gamma = 90^\circ$) the photometer detects still some radiation, while the camera does not. Since total luminous flux is similar in both measurement, a lower value of 557 cd versus 582 cd in the normal ($C = 0^\circ, \gamma = 0^\circ$) direction was registered. These differences are illustrated for the ($C = 0^\circ$) plane in Figure 7. For comparison the theoretical luminous intensity of a lambertian source is also shown. Due to the alignment of the LED module 7 cm below the goniometer's centre, the luminous intensity as registered with photometer will be lower than the value obtained from the camera measurement.

Luminous intensity values have also been determined with the far field goniophotometer in 4 C-planes. These results are shown in Figure 8. In the normal ($C = 0^\circ, \gamma = 0^\circ$) direction a value of 610 cd was registered. This value is higher than the value obtained during the near field measurement. This difference is assigned to the different lamp position in the far field goniometer, in which the lamp is mounted in a vertical plane.

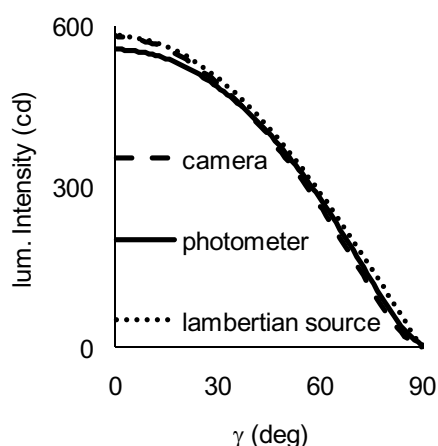


Figure 7. Luminous intensity of a LED module in $C = 0^\circ$ plane as registered with camera (dashed line) and with photometer (solid line).

Besides this, in non-normal directions differences between different planes up to 40 cd were observed for identical γ angles. Here too it is a reasonable assumption that the different rotations in horizontal and vertical planes may affect the luminous output of the LED module. To check the influence of the light source rotations additional measurements are planned with a far field goniophotometer with rotating mirror where the orientation of light source remains fixed.

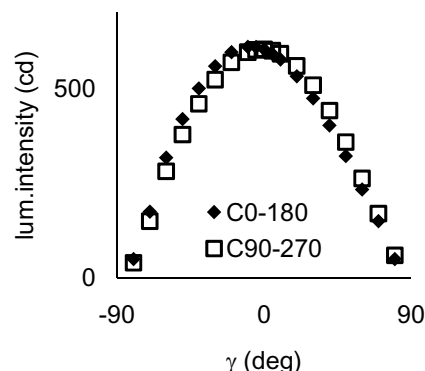


Figure 8. Luminous intensity of a LED module in 4 C-planes as registered with a far field goniophotometer.

CONCLUSIONS

In this paper the possibilities of recently installed near field goniophotometers are illustrated. Measurements were performed on various light sources and results are compared to photometric data obtained during traditional far field goniophotometer tests.

The luminous flux and the luminous intensity were investigated. The luminous flux has been determined using the photometer, resulting in a good agreement with far field data.

On the contrary luminous intensity should be determined with the camera, even when the dimensions of the light sources are small. Luminous intensities as obtained from the test lamps are comparable for both near and far field goniophotometers. Deviations may appear during far field goniophotometry due to the lamp motion in this equipment.

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LUMINOUS INTENSITY DISTRIBUTION AND RAY DATA MEASUREMENT

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ABSTRACT

This article presents an overview of the currently available measuring techniques for determining luminous intensity distributions (LID). Here, particular attention is paid to the intention to show which measuring technique is suitable for what sort of measuring object, just as to point out some certain intersection areas (various measuring techniques applicable to the same measuring object, and vice versa), and where separations have to be made. Furthermore, both common features and differences between the measuring techniques will be presented, and the resulting advantages and disadvantages regarding the measurement of concrete objects will be explained [1].

Keywords: luminous intensity distribution, near field, fourier, ray data

1 LID MEASUREMENT

A LID can be measured both in the near field and in the far field. If the measurement is made beyond the photometric limiting distance, it is called a far-field measurement, otherwise the term near-field measurement applies.

For making LID measurements in the far field, a variety of different measuring techniques is available, which can fundamentally be classified into two groups: the direct LID measuring technique, which includes the different far-field goniophotometers, and the indirect LID measuring technique using luminance measuring cameras.

In the near field, a LID can be recorded by means of a near-field goniophotometer or also a fourier optics. Both systems use a spatially resolved sensor (e.g. CCD), thus being able to detect the point of origin and the direction of rays [2], [3].

2 COMPARISON OF THE MEASURING TECHNIQUES

The full article will point out the advantages just as the disadvantages of the single measuring techniques, thus providing valuable help when choosing the measuring technique in order to fulfil the respective measuring task best. In addition, it contains an overview in the form of a table of the characteristic properties of the various measuring techniques.

Before choosing the measuring technique, probably the most important question is: "Which information is required?" as the various measuring techniques supply quite different items of information.

If, for example, ray data are required, a near-field measurement will be imperative. If, in this case, a full-sphere measurement or a very fine angular resolution is necessary, only near-field goniophotometers can be used. For small objects, restricted angular ranges and low contrasts, also a near-field measurement using a fourier optics can be made. However, if only the LIDs are to be measured, quite various options are available for solving numerous measuring tasks.

For choosing the best suited measuring technique, the user will have to consider a number of criteria such as: the size and the photometric limiting distance of the measuring object, the required accuracy, the angular resolution (measuring grid), the detectable overall range (relevant solid angle), the speed of measurement, and the space required by the measuring instrument or also the measuring set-up. Often, also other factors may play a role, for example the kind of the light source, the contrast in the LID or simply the price of the measuring system.

	far field							near field			
	direct				indirect						
	Luminaire turning device	Goniophotometer with mirror arrangement	Compact-goniophotometer	Kardan-/Robot-goniophotometer	Image processing measurement	Compact measurement setup	Imaging sphere	LED-goniophotometer	Lamp-goniophotometer	Luminaire-goniophotometer	Fourier lens
fix burning position	no	partial	partial	yes	yes	yes	yes	partly	yes	yes	partial
max. size of object	1m	2m	20cm	30cm	1m	20cm	5cm	5cm	30cm	2m	1m
typical measuring distance	10-30m	40m	2m	3m	any; 10m	any; 0.5m	0.3m	any; 10cm	any; 27cm	any; 2m	any
solid angle	sphere				$9\pm30^\circ, \varphi\pm40^\circ$		$\pm90^\circ$	sphere			$\pm88^\circ$
power	any		attend power		any	attend power					
meas. contrast	>1:20.000		<1:20.000		<1:1000		<1:200	<1:500			<1:200
angle resolution	0.01° step size; >0.04° dependent on size of sensor and measuring distance				0.01° depending on size of sensor			0.01° depending on size of sensor			0.06° dependent on size of sensor
measuring time	minutes-hours				seconds			minutes-hours			sec.-hours
size ¹	6	7	4	5	6-1	2-1	2	1	3	4	1
price ²	5-6	5-7	5	-	1	2	3	3	4	5	4

¹ numeration according to size; starting with 1 as smallest² numeration according to estimated costs; starting with 1 as least expensive

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2D SPECTRAL AND LUMINANCE MEASUREMENT DEVICE

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ABSTRACT

This paper introduces a novel design of 2D Spectral and Luminance Measurement Device (2D SLMD) which provides new solution for light and radiation measurement. It employs the hyperspectral imaging technology, and can acquire important quantities, e.g. spectral radiance, luminance and color information in two dimensions conveniently and comprehensively. This paper analyses the factors that affect the performance of a 2D SLMD, and introduces the calibration and correction methods, which are very important for the absolute metrology. The measurement uncertainty of the 2D luminance of an LCD screen is analyzed. The introduced 2D SLMD can obtain satisfactory accuracy.

Keywords: Spectral radiance, imaging, two-dimension, luminance, measurement

1. INTRODUCTION

For displays, luminaires, lighting scenes and so on, the luminance, spectra, color and their two dimensional (2D) spatial distribution and uniformity are important quantities. Note that the 2D spectral radiance is the key for all these quantities. However, current filter-wheel imaging luminance meters can not acquire successive spectral information ^[1]. And common spectroradiometers that only measure single point once can hardly realize the 2D measurement.

To solve this problem, the hyperspectral imaging technology which combines the imaging and spectroscopy technology gives clues. We built a new 2D Spectral and Luminance Measurement Device (2D SLMD), it can measure the absolute spectra of targets in successive 2D luminous surface, and for every point in the surface, the spectra can be measured successively in high resolution.

2. BASIC PRINCIPLE OF HYPERSPECTRAL IMAGING

Hyperspectral imaging is commonly used in remote sensing ^[2]. Fig.1 shows the basic principle of a push broom typed airborne

imaging spectrometer for remote sensing of the ground. There is a detector of two dimensions. One is the spatial dimension corresponding to a line of the ground target. The other one is the spectral dimension, along which the sampled light is dispersed. The imaging spectrometer records all spectra across a spatial line simultaneously. An aircraft flies along a direction perpendicular to the line for scanning, so as to record sequential lines and build up hyperspectral images in two spatial dimensions.

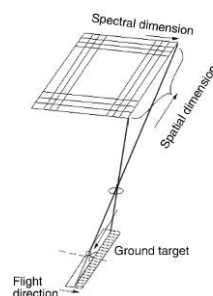


Figure 1. Basic principle of a typical airborne imaging spectrometer.

3. NEW DESIGN OF A 2D SLMD

A 2D SLMD which employs the hyperspectral imaging technology is introduced for the measurement of displays, luminaries, lighting scenes and similar objects.

Fig. 2 shows a design of 2D SLMD, it consists of an imaging system, a 2D spectroradiometer, a scanning device, a visual alignment system and a micro-processing unit (MPU). The imaging system takes an image of a 2D target on the slit surface of the 2D spectroradiometer. There is a reflecting mirror as a shutter set in front of the slit. It reflects the light from the 2D target to the visual alignment system. During the measurement, the reflecting mirror moves away, and the slit passes only the light from the measured line. The 2D spectroradiometer provides full, successive spectral data for each pixel in a 2D array detector, so as to acquire the spectra of each point in the line. The scanning device makes the slit move relatively to the target for switching the lines. The scanning device

and the 2D spectroradiometer are both controlled by the MPU. They can couple each other precisely to acquire absolute hyperspectral radiance of the measured target.

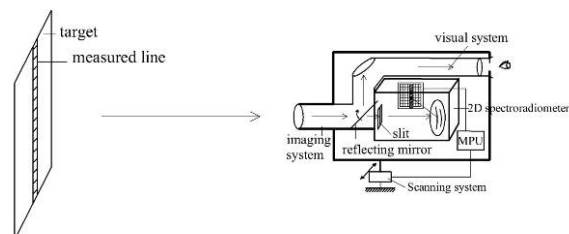


Figure 2. Schematic diagram of a 2D SLMD.

Fig. 3 shows a prototype of 2D SLMD which is under research and improvement. The structure of the prototype device is a little different from the schematic diagram now.

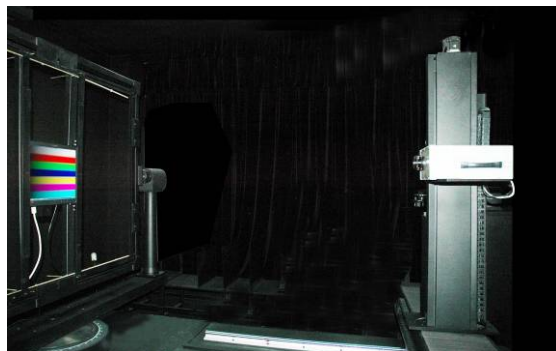


Figure 3. Picture of a prototype of 2D SLMD.

4. DATA PROCESSING

The data processing software of 2D SLMD provides measurement results, including spectra, luminance, color information and hyperspectral images.

As above described, a 2D SLMD obtains the spectral radiance of 2D objects, together with the spatial dimension. The 2D spectral radiance is expressed in three dimension (3D), i.e. $L_e(x, y, \lambda)$. Fig. 4 shows the data structure. In the cubic, y axis represents the spatial dimension of the 2D array detector, which is the direction of measured line in Fig.2. And x axis corresponds to the scanning direction, it relates to the time. The shadowed plane and the paralleled ones in fig.4 are sample planes. They record measured data of each sampling.

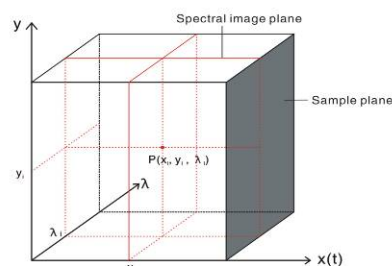


Figure 4. Data structure of spectral radiance.

The data structure cubic can be transferred to a hyperspectral image which can describe the spatial spectral radiance $L_e(x, y, \lambda)$ vividly.

As the scanning interval is usually smaller or larger than measured area of each sampling, there are gaps or overlap along x axis accordingly. That brings problems when merging the sample planes to a hyperspectral image. Interpolations can be applied to solve the gap problem in a certain degree.

The luminance and colorimetric quantities in 2D are obtained by integrating the 2D spectral radiance according to the CIE photometry and colorimetry theory.

5. CALIBRATIONS, CORRECTIONS AND UNCERTAINTY ESTIMATION

5.1 Factors affecting the performance

Both the imaging and spectral characteristics determine the performance of a 2D SLMD.

As shown in Fig. 3, the spatial resolution along the x axis is determined by the instantaneous field of view (IFOV) of the 2D SLMD which depends on the imaging system and the slit width of the 2D spectroradiometer. And the spatial resolution along y axis is mainly determined by the pixel size of array detector. Spatial resolutions can be expressed by angular with radian unit, mrad. Generally, the spatial resolution is the higher the better. However, too high resolution decreases the signal to noise ratio (SNR), and consequent affects the spectral measurement accuracy, meanwhile, it influence the measurement speed as the integrating time is increased.

The spectral measurement performance includes spectral range, wavelength accuracy, spectral resolution, stray light, linearity and dynamics, etc.. These specifications are mainly determined by the

2D spectroradiometer which is well known in light measurement. In the design described in Fig.2, the spectral range is visible from 380nm to 780nm. The spectral bandpass is 3nm. The 2D array detector is a thermal-electric (TE) cooled CCD with 1024(spatial) × 1024(spectral) pixels. It has relatively low dark noise and wide dynamic range, which can be enhanced by adjusting integration time of the 2D spectroradiometer according to measured optical signal.

The crosstalk between neighbouring pixels and straylight shall be noticed as it affects both the spatial and spectral accuracy.

5.2 Calibration of spectral radiance

The 2D SLMD measures absolute quantities, hence the calibration of goodtraceability is very important. Fig. 5 shows a typical calibration scheme for a 2D SLMD.

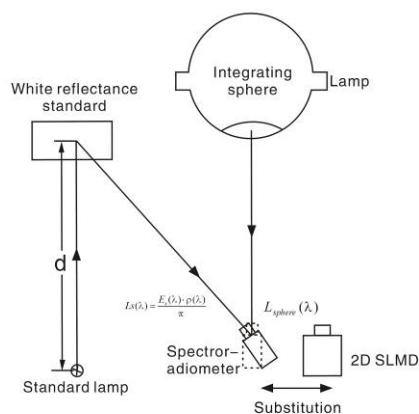


Figure 5. Typical calibration scheme of a 2D SLMD.

The combination of spectral irradiance standard lamp and the white reflectance standard provides standard spectral radiance $L_s(\lambda)$ that are traceable to National Metrology Institute, $L_s(\lambda)$ is calculated as:

$$L_s(\lambda) = \frac{E_s(\lambda) \cdot \rho(\lambda)}{\pi} \quad (1)$$

Wherein, $E_s(\lambda)$ is the known spectral irradiance of the standard lamp, $\rho(\lambda)$ is the known reflectance of the white reflectance standard.

A spectroradiometer is used to transfer spectral radiance quantities by an integrating sphere source. The integrating sphere source provides a lighting surface with uniform and stable spectral radiance $L_{sphere}(\lambda)$, and the luminance L_{sphere} is a

integration value of $L_{sphere}(\lambda)$. The 2D array detector is overfilled.

The calibration uncertainty of luminance is analysed in table 1.

Although the uncertainty of spectral irradiance of the standard lamp at wavelength around 350nm 1.3% (K=2), this part contributes little to the integrated luminance value. Thus the uncertainty factor takes 0.9% (K=2) which corresponds to the value of wavelength from 400nm-780nm.

Table 1. Calibration uncertainty of luminance.

Uncertainty factors	Uncertainties (K=1)[%]	
	Type A	Type B
NIST spectral irradiance standard lamp		0.45
Long term drift of standard lamp		0.1
Standard lamp stability	0.05	
White reflectance standard		0.35
Long term drift of reflectance standard		0.15
Error of distance d	0.1	
Spectral accuracy of the spectroradiometer		0.15
Reproducibility of the spectroradiometer	0.1	
Linearity of the spectroradiometer		0.1
Stability of the sphere source	0.1	
Non-uniformity of the sphere source		0.25
Wavelength error of the 2D SLMD		0.05
Stray light of the 2D SLMD		0.3
Expanded combined uncertainty (K=2)	1.48	

5.3 Corrections

5.3.1 Linearity correction

Change the luminance level of a stable and uniform surface whose spectral radiance is known, e.g1. the illuminated white reflectance standards or the integrating sphere in fig.5. Comparing the known standard quantities $L_s'(\lambda)$ to the measured values of the 2D SLMD $L_t'(\lambda)$ to give the correction factor:

$$C_l = \frac{L_s'(\lambda)}{L_t'(\lambda)} \quad (2)$$

The luminance levels varies in multi magnitudes, so as to acquire correction factors in a wide dynamic range. The integration time of the 2D spectroradiometer can be changed during the calibration, which can also be altered in the measurement according to the practical radiance. This solution widens the dynamic range of the 2D SLMD.

5.3.2 Image aberration correction

Scanning the 2D SLMD to acquire the 2D spatial spectral radiance stable and uniform surface, correcting the measured value of the same λ coordinate to be the same. This correction is especially useful for the measurement of a flat source or object, and reduces the error cause by crosstalk in a certain degree.

It shall be noted that, the spatial resolution is not uniform when the scan is completed with the meter rotating. As shown in Fig. 6(a), the dimension along y axis is uniform, because elements in the measured line correspond to pixels of the 2D array detector which usually have the same size. However, the width of measured lines is not the same for every scan as Fig. 6(b), it increases along with the scan angle φ . Take O as the origin point (Fig. 6), the x value at scan angle φ is $l \cdot \tan \varphi$, when φ changes linearly during the scan. To acquire quantities distributed along x axis with the same intervals, tangent correction and interpolation is necessary.

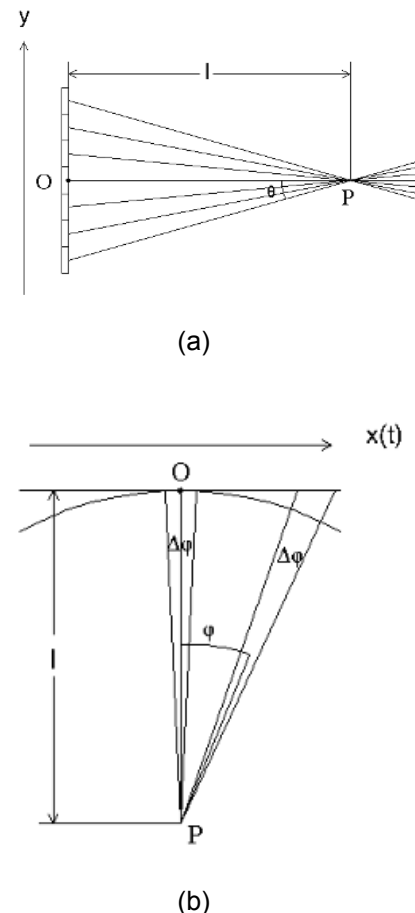


Figure 6. Data structure of spectral radiance.

5.3.3 Other corrections

There are also some other corrections to enhance the measurement accuracy, for example, stray light correction^[3]. They are not introduced in detail in this paper.

5.4 Measurement uncertainty budget

Here we take the measurement of an LCD screen displaying uniform white light as an example.

Table 2. Uncertainty budget of measurement of spatial luminance of a LCD.

Uncertainty factors	Uncertainties (K=1)[%]	
	Type A	Type B
Calibration uncertainty		0.74
Instability of the target	0.8	
Linearity ^{*1)}		0.1
Image aberration ^{*2)}		2
Stray light of 2D spectroradiometer		0.25
Spectral bandpass		0.15
Crosstalk	0.5	
Polarization		0.5
Instrument stability	0.1	
Wavelength accuracy		0.1x
Expanded combined uncertainty (K=2)	4.78	

^{*1)} After linearity correction

^{*2)} Can be reduced by sophisticated optics and mechanics

CONCLUSIONS

This paper introduces a novel design of 2D SLMD for luminous surface measurement. It employs hyperspectral imaging technology, and can acquire the spectral radiance, luminance, colorimetric quantities of an arbitrary target in a successive 2D surface.

There are many problems, such as the image aberration, stray light, cross talk, photoelectronic linearity and dynamic range. By further research and development, the performance of 2D SLMD can be obviously improved.

The 2D SLMD is believed to be widely used in the future due to its advantages, from space to civil industries.

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HYPERSPPECTRAL IMAGING DEVICE FOR COLOUR MEASUREMENTS

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ABSTRACT

At the National Institute of Metrological Research (INRiM) a hyperspectral imaging (HI) device based on a scanning Fabry-Perot (F-P) interferometer has been realized.

The F-P interferometer is made of two glass mirrors mounted in aluminum frame and the distance between the mirrors is scanned by means of three piezo actuators. During the cavity length scanning the instrument records a sequence of pictures (a video). For each pixel an interferogram is obtained from the video processing and elaborated to give the spectral composition of the radiation hitting the same.

The potentiality of the instrument has already been demonstrated in the visible region and in the near-infrared region in [1] and [2] respectively. The first results obtained in the visible region with a new, more compact version of the instrument are presented.

Keywords: hyperspectral imaging, spectral analysis, colour measurements, interferometer

1 INTRODUCTION

Hyperspectral imaging (HI) is a powerful method of analysis to obtain the spectral composition of the radiation emitted by a subject. A HI device is typically made of a spectrophotometer and an imaging device. The obtained data set is known as "hyperspectral cube" and it is a 3D matrix formed by a 2D image to which is associated the spectral composition of each pixel.

Development of HI devices is growing due to the increasing numbers of applications, for example satellite Earth survey, spectroscopy, colorimetry, thermal imaging and so on. Classical HI devices are usually made by integrating a dispersive means (a prism or a grating) or a tuneable band-pass filter in an optical system. These devices have a good image quality and resolution but also a low efficiency in terms of photon collection. A comprehensive overview on classical HI devices can be found in [3].

When the spectrometer is based on an interferometer instead of a dispersive means

there are two features that make this system a faster (or equivalently with higher luminosity) instrument when compared to the others at the same resolution. First, the Fellgett or multiplex advantage arises from the fact that there is no spectral scanning and all the spectral components are acquired at the same time. Second, the Jacquinot or throughput advantage originates from the fact that the apertures used in the interferometric spectrometers have a larger area than the slits used in dispersive spectrometers, thus enabling higher throughput of radiation. On this basis, novel techniques using Michelson or Sagnac interferometer have been developed with interesting results as described in [4] and [5].

At INRiM a hyperspectral imaging device based on a Fabry-Perot interferometer has been realized. By applying an algorithm based on the Fourier transform (FT) to the interferogram it is possible to obtain the spectral composition of the subject. Here we present the results obtained in the visible region (400-720 nm), with the new version of the instrument.

2 HYPERSPPECTRAL IMAGING DEVICE

The hyperspectral imaging device is made by a F-P interferometer inserted in a simple optical system formed by a monochromatic camera and a photographic objective (Fig. 1).

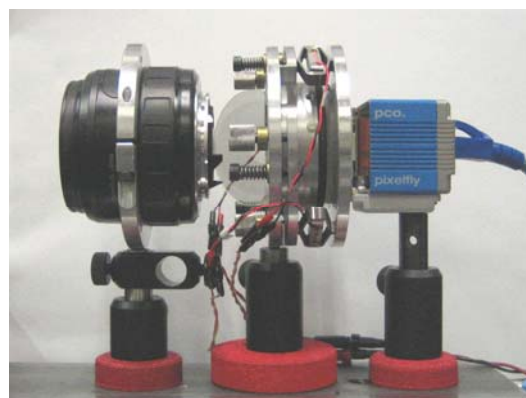


Figure 1. Picture of the hyperspectral imaging device. From the left: the photographic objective, the F-P interferometer and the monochromatic CCD camera.

2.1 The F-P interferometer

The F-P interferometer is the core of the HI device. It is made of two glass mirrors coated with a thin aluminum layer having a reflectivity around 25%, mounted in an aluminum frame. The distance between mirrors is varied from zero to 40 μm by means of three piezo actuators. During the cavity length scanning a video is captured so the variation of light intensity on each pixel is recorded.

The recorded data are then analyzed to obtain an interferogram from which it is possible to calculate the spectral composition of each pixel by applying a Fourier transform based algorithm. In order to apply the FT it is necessary to know the distance between the mirrors for each frame

of the video. This calibration is carried out by analyzing the interferogram of the pixels when illuminated by a monochromatic light (a laser) as described in 1.

2.2 Experimental setup

As described before, the HI system is made by a photographic objective, the F-P interferometer and a 12-bit CCD camera. The camera has been modified in order to place it as close as possible to the F-P interferometer (Fig. 1). In front of the photographic objective there is a 400 to 720 nm band pass filter needed to select the wanted portion of spectrum. The layout of the experiment is schematized in Figure 2 and a picture of the experimental setup is presented in Figure 3.

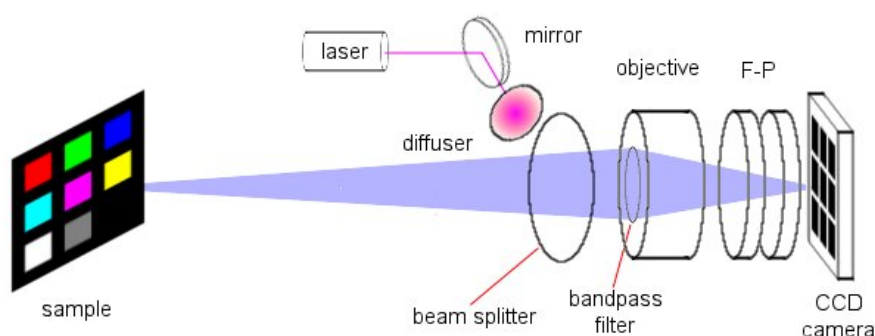


Figure 2. Schematic layout of the experiment. From the left: the light emitted (or reflected) by the sample is focused on the CCD camera sensor after passing through a beam splitter, the photographic objective and the F-P interferometer. The blue laser used to calibrate the mirror distance is diffused on the beam splitter just in front of the objective by means of a mirror and a diffuser. (In case of reflected light to the scheme must be added an illuminant for the sample).

In the experimental setup presented, the sample is a 9 coloured square pattern displayed on a 13" LCD with LED backlight. The display is placed normal to the HI system at around 1 m distance from the camera sensor.

This prototype has an important improvement with respect to the previous prototype described in 1. In the previous prototype in order to calibrate the mirror distance the sample is illuminated with a reference laser and from the measured interferogram it is possible to obtain the optical path difference (OPD). In the present prototype the laser is sent to a diffuser close to the beam splitter in front of the photographic objective. In this way

the diffused image is not focused on the CCD, where the subject is focused, but further out.

Results show that calculation of the spectral distribution is possible even if the reference laser is not on the sample, This is particularly important because it means that it is possible to integrate the reference directly in the hyperspectral imaging device to realize a more compact instrument. Furthermore, with this prototype is possible to recover the spectrum of a sample at great distances without the need of having a reference on it simply by changing the photographic objective.

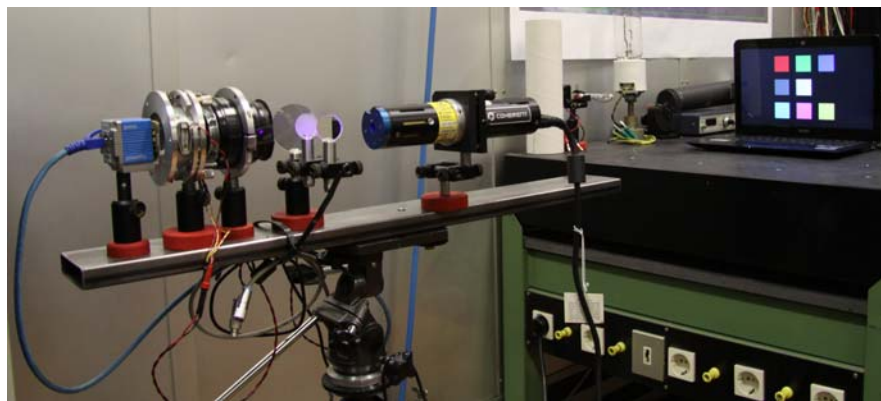


Figure 3. Detail of the experiment. From the left: on the tripod the hyperspectral imaging system and the blue laser, at the right on the table the notebook with LED backlight display used to view the coloured pattern used as a target.

2.3 Calibration and acquisition

Unlike previous experiments, where the reference laser had to be present on the object to be imaged (as described in 1), here two videos have been recorded consequently: the first one is the video of the monochromatic source for calibration and the second one is the video of the target sample displayed on the notebook. The video frames of the two videos are triggered in such a way that they are synchronous with the mirror distance scan.

The videos have been acquired in a darkroom to minimize the effect of stray light, so the only light sources were the reference laser and the display of the notebook. The resulting images captured are shown in Figure 4.

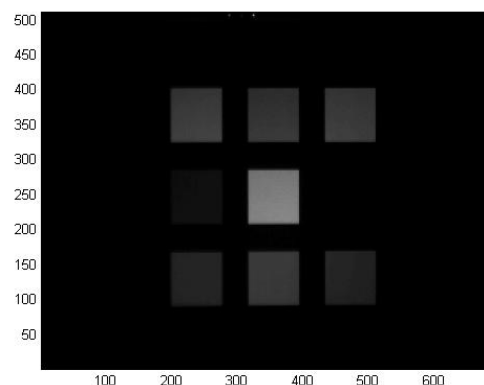
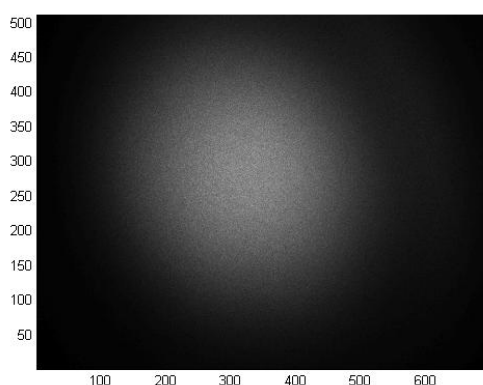


Figure 4. First frame of the two videos. Above the diffused calibration laser and below the pattern displayed on the notebook screen.

3 RESULTS

For each square of the pattern a 10x10 pixel area has been considered to obtain the spectral composition.

Since the spectral response of the HI system is unknown it is necessary to normalize the obtained spectra with respect to a known spectrum, in our case the spectrum of a white screen measured with a calibrated commercial spectroradiometer with 1 nm resolution. The ratio between the spectrum measured with the spectroradiometer and the same obtained with the HI system gives the normalization function.

3.1 Emission spectra

In order to validate the results, the calculated spectra have been compared with the reference spectra measured with the spectroradiometer.

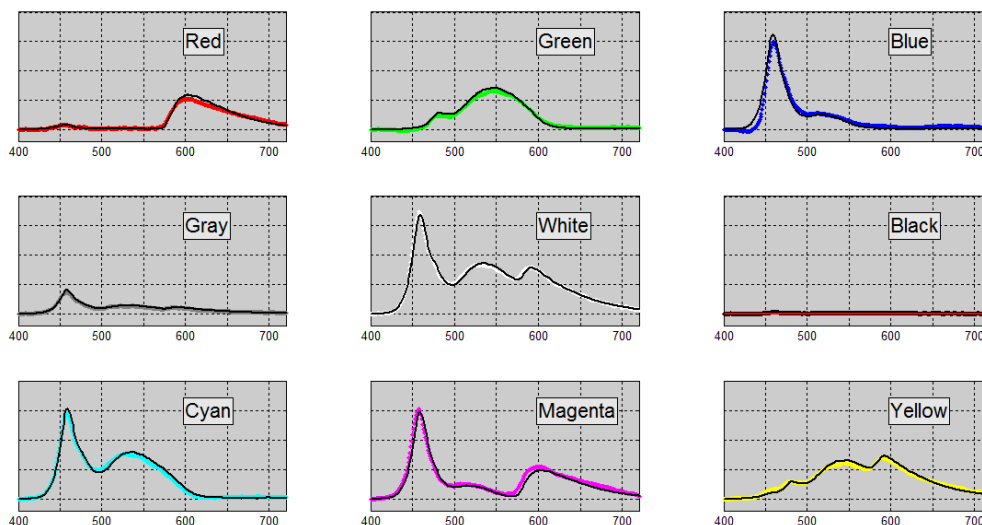


Figure 5. Emission spectra obtained with the HI device (coloured) compared with corresponding measured with the spectroradiometer (black).

The spectroradiometer has been placed normal to the display at 2 m distance. The aperture angle of the spectroradiometer was 0.1° so the measured area is comparable with the one considered with the HI system. The comparison between the spectra is presented in Figure 5. It is possible to see that there is a good overlap between the two spectra.

4 CONCLUSIONS

With this new experimental setup we have confirmed the results obtained with the previous prototype and presented in 1, where the reference laser illuminated directly the sample. In this new setup the reference laser shines a diffuser instead of the sample and whose image is not on the image plane. This set-up permits the realization of a self calibrating, compact instrument.

The comparison with the commercial spectroradiometer highlights the potentiality of the instrument with significant results even in this experimental conditions. Unlike commercial spectroradiometers, that give the spectral distribution by measuring a small homogenous area, our device is capable of giving the spectral composition of each pixel of the image captured. This is particularly interesting because this allows spectral analysis of complex subjects in a single acquisition.

In the end, as already been demonstrated in [2], the instrument is capable of giving the spectral composition in different spectral regions by changing only the elements of the optical system (the camera, or the photographic objective) allowing, for example, thermal imaging or spectroscopy when operating in the infrared [6].

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CCD-CAMERA FOR MEASURING TEMPERATURE AND SPECTRAL RADIANCE

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ABSTRACT

The application of thermal imagers to measure the two dimensional distribution of temperature in the mid- to far- infrared spectral range is an established technique. However, this wavelength range is not well suited for temperatures exceeding 1000°C.

For higher temperatures the application of imaging systems operating in the visible or even near UV spectral range is the method of choice. Although the application of imaging systems at these wavelengths for measuring two-dimensional distributions of luminance has already reached a sophisticated level of accuracy, up to now such systems used to measure temperatures and the absolute spectral radiance have not yet been widely and traceably applied.

In this paper we describe the thorough investigation of a CCD based camera system equipped with a filter wheel for traceable temperature and spectral radiance measurement at temperatures above 1000°C.

Applying such a camera system for the absolute measurement of temperature and spectral radiance requires specially adapted filters and optics. However, in contrast to point measure systems the application of interference filters causes problems when using a focal plane array as detector for measuring two-dimensional distributions of temperature and radiance. Therefore, prior to the application of the camera, the usability of this camera system for the measurement of the radiance of high-temperature black bodies and their ability to absolute calibration have been tested.

Keywords: Imaging Radiance Measuring Device (IRMD), CCD, High Temperature measurement

1. INTRODUCTION

The use of imaging techniques in imaging luminance and imaging colour measuring systems is widely accepted. The aim of the

authors is to use an adapted version of this technology for absolute temperature measurements and for the characterisation of radiance temperature standards like high-temperature blackbodies (HTBB).

In the article the camera system and their components are explained in the second section. After a model based characterisation of the system in the third section, measurement results using a high-temperature furnace HTBB are presented in the forth section.

2. CAMERA SYSTEM

Based on a CCD filter wheel system a radiance camera for absolute temperature measurements was developed. For this purpose, beside a clear window (representing the original CCD responsivity) five metal interference filters are used with central wavelengths of approx. 450 nm, 500 nm, 650 nm, 800 nm, and 900 nm, respectively, each having a bandwidth of approx. 10 nm FWHM.

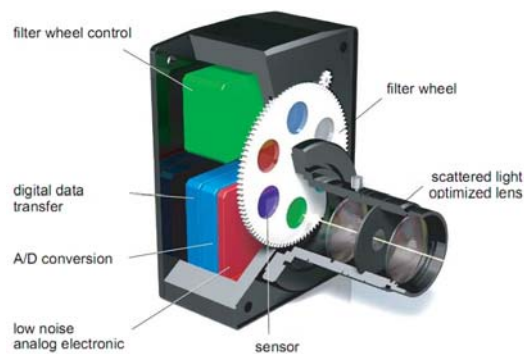


Figure 1. Principle drawing of a filter wheel system for the radiance camera

One standard 100 mm lens and an image-side telecentric macro lens were calibrated in a standard calibration procedure for imaging colour measuring devices. Furthermore, different neutral density filters made from glass (absorptive filters) and neutral density filters based on semitransparent metallic mirrors (reflective filters) are used to adapt the measurement range of the system for all filters to the high

dynamic range of the spectral radiance for a wavelength range from 450 nm to 900 nm and the temperature range from 1000°C to 3000°C.

3. CHARACTERISATION

In a first step and as a basis for the estimation of the measurement uncertainty the camera system was characterized according to 1. . The modelling of the camera system is carried out by the model described in 2. .

The spectral responsivity of the system was measured for the complete camera system. Additionally, the spectral transmittance of the metal interference filters and the neutral density filters were measured separately.

For all measurements the linear temperature coefficients (for the spectral responsivity of the camera system and for the spectral transmittance of the filter) and the uniformity across the filter and across the CCD array were evaluated.

3.1. Properties of lenses

The design of the lens determines the angular direction of rays before and after the lens.

For the neutral density filter in front of the lens (Fig. 2 (2)) the position and size of the entrance pupil is of interest. There is an angular variation depending on the pixel position, but in most cases the calculation can be done with the angle of the central ray.

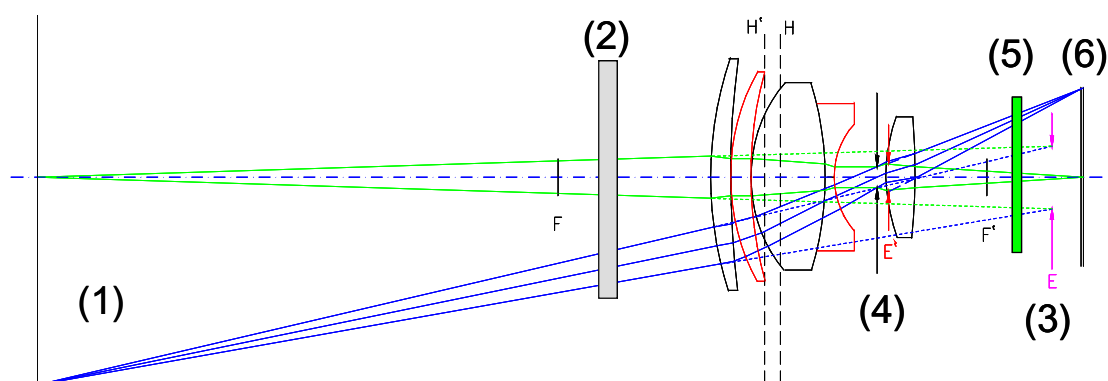


Figure 2. Lens section for a 100mm lens (H,H' main plains and (1) scene (2) neutral density filter in front of the lens (3) entrance pupil (4) exit pupil (5) filter for spectral matching (6) sensor)

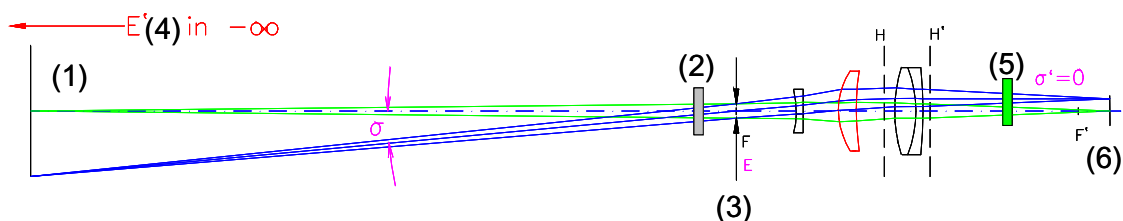


Figure 3. Lens section for a macro lens with exit pupil position E' in $-\infty$ (image-side telecentric) before the lens and small angular variations at the Sensor.

For the filter behind the lens (usually used for the spectral responsivity matching) the position and size of the exit pupil is of interest. Figure 2. and Figure show that the angular distribution of the rays varies in a wide range and for the calculation of the angular dependence the distribution of the rays is of interest and must be considered.

3.2 CCD-modelling

Based on the work of Janesick 5. , 6] and the current work in 1], a matrix of luminance/radiance values L that is measured with imaging devices can be modelled as follows:

$$L = \frac{k_L}{P_L} E'_e; \quad E'_e = \frac{S - \bar{D}}{k_{Sys} \cdot t_l \cdot A_p \cdot \bar{P}} \quad (1)$$

where k_L is the luminance/radiance calibration factor, E'_e the effective irradiance at the CCD and $\bar{P}_L$ the lens shading.

The irradiance E'_e is determined as the measured light signal S corrected for the measured dark signal $\bar{D}$ and the, the system transfer factor k_{Sys} , the integration time t_i , the pixel area A_p and the CCD shading $\bar{P}$ are taken into account. The measured signal S can be written as the sum of a light signal S_E and a dark signal $\bar{D}$, resulting in $S = S_E + \bar{D}$, which is detailed according:

$$S = \underbrace{k_{Sys} \cdot t_i \cdot A_p \cdot \bar{P} \cdot E'_e}_{S_E \text{ (light signal)}} + \underbrace{k_{Sys} \cdot (Q_{DS0} + N_R + t_i \cdot I_{DS}(T)) + S_{off} + N_Q}_{\bar{D} \text{ (dark signal)}} \quad (1)$$

$$u^2(S) = u^2(S_E) + u^2(\bar{D}) + 2r(S_E, \bar{D}) \cdot u(S_E) \cdot u(\bar{D}) \quad (2)$$

The dark signal $\bar{D}$ depends on the dark signal offset Q_{DS0} at the integration time $t_i = 0$ s, the dark signal generation rate $I_{DS}(T)$ (dark current, depending on the CCD-temperature T and integration time / integration mode) the reset noise of the charge to voltage converter N_R , the quantization noise of the analogue to digital converter (ADC) N_Q and the signal offset S_{off} . **Bold** values describe matrices as image data and values denoted $\bar{X}$ represent mean values from various images to reduce the temporal noise by signal averaging.

The uncertainty estimation in Eq. (3) is given with the correlation between the measured light and dark signals.

Resulting from the Poisson distribution of the signal (counting photons) we can use the following model¹ function to calculate the signal noise depending on the signal level S with the temporal dark signal noise σ_0 and the constant factor F for consistency in the units.

$$\sigma^2(S) = k_{Sys} \cdot F \cdot S_E + \sigma_0^2 \quad (3)$$

Equation (4) is the basic equation for the Photon Transfer Method (PTM, [6]). This

¹ The unit correction factor $F = e^-$ is necessary to correct the mathematical relation $E\{X\} = D^2\{X\}$, for Poisson distributed random numbers. The physically correct unit is obtained.

basic equation is used for all uncertainty estimations to model the signal-to-noise ratio for the measured images.

3.3 Spectral responsivity of the CCD

By using the glass filter in the filter wheel the spectral responsivity of the CCD (including the lens characteristic and the glass filter with the anti-reflection coating) has been measured (Fig. 4).

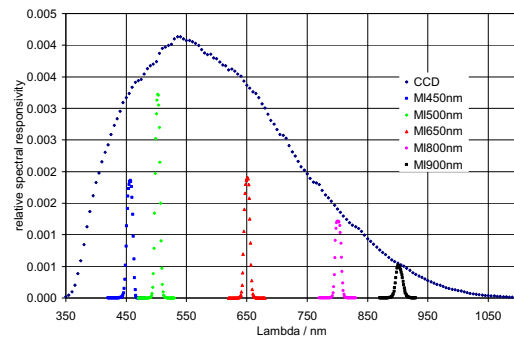


Figure 4. Relative spectral responsivity of the CCD (filter position glass) and all metal interference filters (25°C, 0.8 nm FWHM for the measurement system)

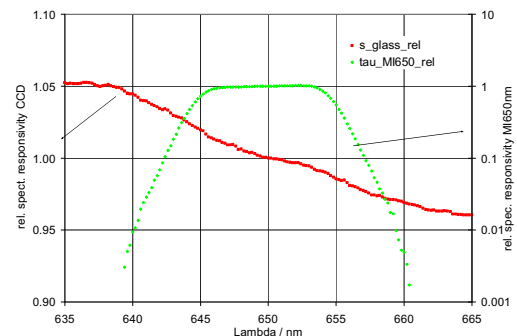


Figure 5. Relative spectral responsivity of the CCD (at filter position "glass") and relative spectral responsivity of the filter position "MI650" (25 °C, 0.8 nm FWHM for the measurement system)

The example (Figure 5.) shows the relative spectral responsivity of the CCD with the glass filter and the 650 nm metal interference filter, respectively. Apparently, the camera can resolve the spectral responsivity signal only within three decades. Therefore, a separate measurement of CCD and filter transmission is recommended. For the glass filter the change of the spectral responsivity has to be taken into account even in the small wavelength range of the single metal interference filters. Depending on the wavelength and bandwidth for the measurement a fine structure in the spectral responsivity can be observed. This fine

structure is different for different positions of the sensor.

3.4 Spectral transmission of the metal interference filters

As explained in the section before, for the characterisation of the metal interference filters a separate measurement of the filter transmission is recommended. The dynamic range of this measurement is some decades better compared to a characterisation of the camera's spectral responsivity with the interference filter. For the system characterisation a combination of both measurements (camera responsivity and filter transmission) is used.

Especially for the use of the data together with the camera responsivity the incidence angle is important. This has already been shown the principal data presented in 4., and can be seen in the lens sections in Figure 2. and Figure and in the measurement example in Figure 7..

Furthermore the temperature dependence is of interest. As an example, the centre wavelength of the MI650nm filter changes by 0.02 nm/K. Considering the filter heats up by 10°K during the measurement this would result in an error of about 1 K at a measured temperature of 2700°C.

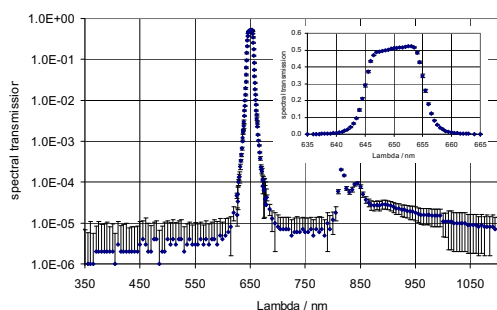


Figure 6. Spectral transmittance with expanded uncertainty of the 650 nm filter

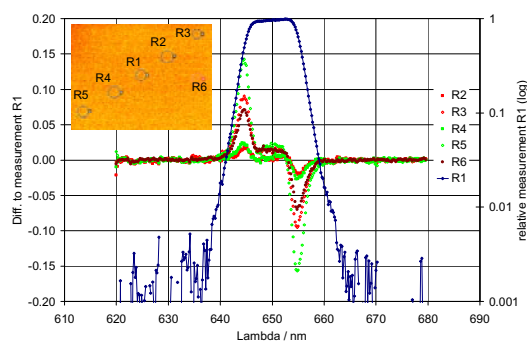


Figure 7. Relative spectral responsivity for different image regions of the MI650nm filter

In Figure 7. the difference in the relative spectral responsivity of seven filter regions with respect to the centre region R.1 is plotted on the left y-axis and the logarithmic relative spectral responsivity of the region R.1 is plotted on the right y-axis as the reference value. The data shows a high variation of the spectral responsivity values. This deviation has to be taken into account for the camera calibration.

3.5 Spectral transmittance of the neutral density filters

Neutral density filters are necessary to adapt the measurement system to the wide radiance range between 1000 °C and 3000 °C. There are two possible solutions:

1. Filters made from glass (absorption filters)
2. Filters made from semitransparent metallic mirrors (reflection filters)

Fig. 8 lists a typical spectral transmission curve for both filter types.

For the blocking glass filters the non-transmitted radiation is absorbed and causes the filter to heat up. These filters have a relatively high temperature coefficient of the spectral transmission and the spectral transmission of the filter varies largely with wavelength. Both may cause problems for the measurements.

Blocking metal interference filters on the other hand have a flat spectral transmission and a low temperature coefficient. The back reflections to the object can influence the measurement and for these filters also the angular dependence of the transmission has to be taking into account.

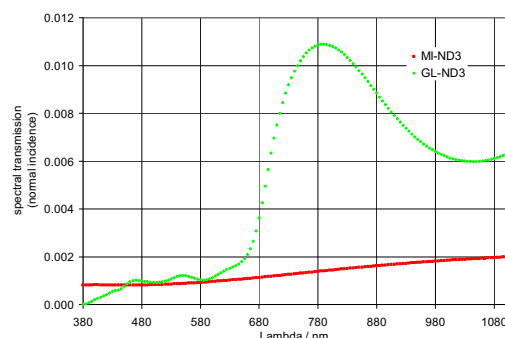


Figure 8. Spectral transmittance of two neutral density filters, a metal interference filter MI (red) with $\alpha_{\text{NLA}} \approx 0.02\% / K$ and a glass filter GL (green) with $\alpha_{\text{NLA}} \approx 0.2\% / K$, both with an optical density of about 3.

4. MEASUREMENTS AT A HIGH-TEMPERATURE BLACK BODY SOURCE

After the spectral characterization, the camera response was investigated for temperatures between 1000 °C and 2700 °C utilizing a high-temperature black body (HTBB) as transfer source for thermal radiation.

4.1 Temperature measurements

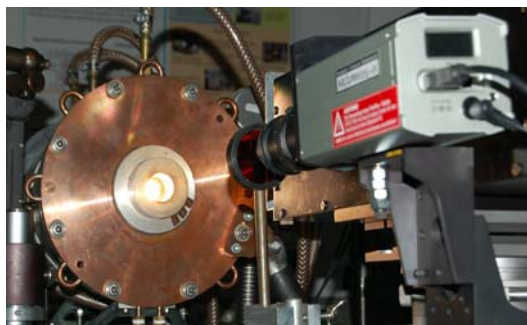


Figure 9. Radiance camera in front of the high temperature furnace BB3200pg

The data was evaluated with a fit formalism according to the Jung/Verch, Hattori-Sakuma equation 3. given in (4) and (5) with the second constant of Planck's law of thermal radiation $c_2 = 0.014388$ mK. Here, the fit parameters A , B , and C allow the user to calculate the temperature T from the camera signal S .

$$S / S_{2856K} = \frac{C}{\exp\left(\frac{c_2}{AT + B}\right) - 1} \quad (4)$$

$$T = \frac{1}{A} \left(\frac{c_2}{\ln(C / (S / S_{2856K}) + 1)} - B \right) \quad (5)$$

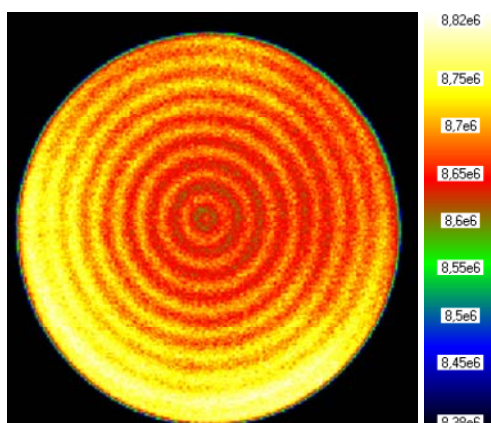


Figure 11. Radiance camera focussed onto the bottom plate of the HTBB furnace

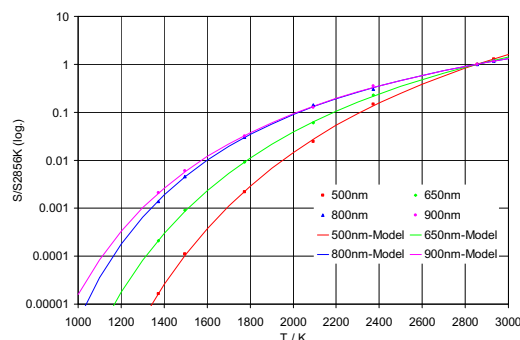


Figure 10. Relative signal from the camera system for different filters (marked points) and the model fit (solid lines) for the HTBB measurements

The 450 nm interference filter was found to be of poor quality with respect to the field uniformity and stability of the spectral transmission. Therefore, the measurements with this filter have not been considered here.

4.2 Homogeneity of the BB3200pg

The homogeneity of the BB3200pg was investigated while focusing on the bottom plane of the HTBB. This is not a correct use of the HTBB (the focus position is usually on the front opening), but it shows a possible application of the IRMD for the uniformity evaluation.

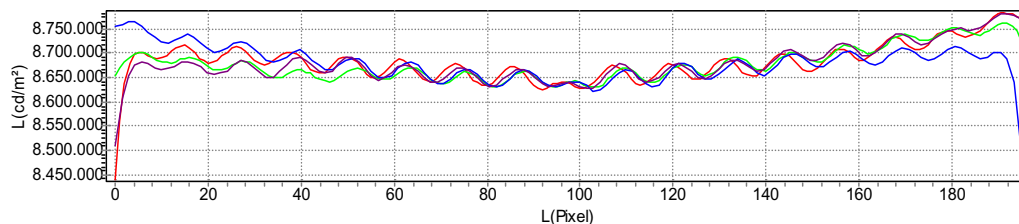


Figure 12. Sectional views for the luminance at the bottom of the HTBB furnace

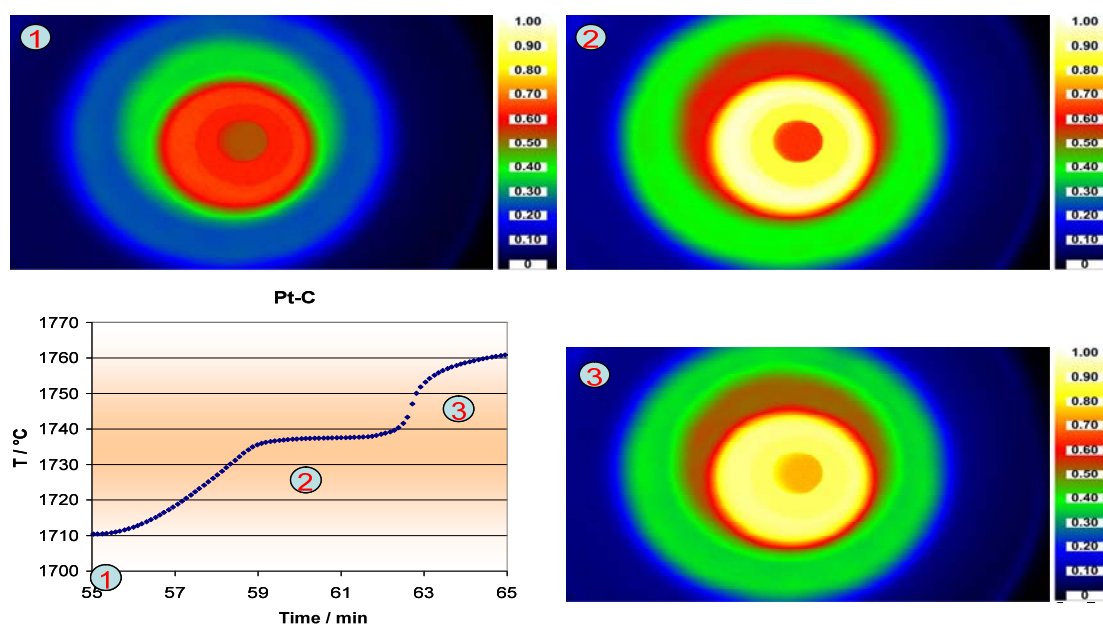


Figure 13. Small aperture Pt-C fixed point cell in Nagano type furnace before, during and after the melting plateau

Figure 13. shows a good example for the use of the camera system for small objects. Here, a Pt-C fixed-point (1738 °C) [9] is installed into a high-temperature furnace and the camera detects the surrounding furnace area in front of the fixed-point and the fixed-point's cavity aperture (3 mm in diameter). With the camera system a selection of the evaluation area can be made using the surrounding information in the image. Furthermore one can use the surrounding information to estimate the influence of this surrounding on the measurement results, e.g. by calculating an effective radiance profile before, during and after the melting of the fixed-point metal (Size-of-Source effect). This is an advantage over single point measurement systems as melting is a dynamic process and a temperature profile at a specific time can otherwise not be measured.

5. SUMMARY

With the first measurement results shown here the authors demonstrate the usability of the imaging technique for evaluations in the field of high-temperature measurements.

Further evaluations have to be done for the estimation of the measurement uncertainties associated with the temperature and spectral responsivity measurements. Furthermore some angular dependency effects of the metal interference filters are not yet fully understood. Here additional evaluations and advanced modelling is necessary.

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HIGH ACCURACY CALIBRATION OF OPTICAL SPECTROMETERS (HICALOS)

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ABSTRACT

High spectrometer calibration accuracies are key for a wide range of applications. Typically, one calibrates the spectrometer with a calibration lamp, providing distinct and well defined calibration lines. However, for small spectral ranges, where only one or two calibration lines are present, the calibration becomes inaccurate. Furthermore, the accuracy of the calibration may locally vary according to the number of nearby calibration lines and their different intensity. In this paper we present a high precision non-linear wavelength calibration method, which requires only two or less reference lines from a calibration lamp and one additional passive optical element.

Keywords: spectrometer, calibration.

1. PASSIVE CALIBRATION ELEMENT

The additional key element introduced is a Fabry-Perot multilayer structure, as shown in Figure 1 below, which yields multiple sharp transmission maxima of similar intensity over the full spectrometer range under broad band illumination (e.g. white light source).

In this example, the spectrometer is read out by a multi-pixel CCD. The wavelength of each pixel is theoretically described by a non-linear spectrometer dispersion equation. The recent trend to more miniaturized spectrometers introduces a higher degree of non-linearity.

The idea is to illuminate the spectrometer with a conventional calibration lamp as well as a white light lamp that is filtered by a Fabry-Perot structure. With this method, one obtains an optimal coverage of the spectral range with reference lines of similar intensity and adjustable peak-to-peak separation and peak width. The equal illumination of the spectrometer grating by both sources is of utmost importance for a high calibration quality. Both sources, 1) and 2), are therefore coupled into the miniature spectrometer via the same optical fibre.

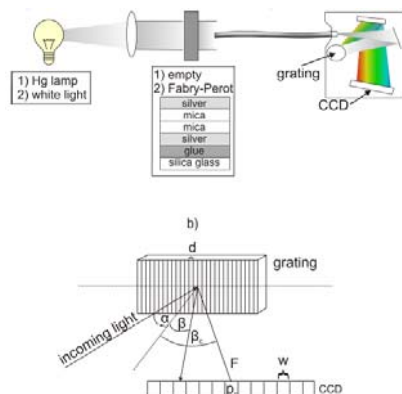


Figure 1. Schematic illustration of calibration setup and multi-layer structure used.

2. FINDING THE UNIQUE SOLUTION

An iterative algorithm is put forward to obtain a self-consistent calibration of a few picometer accuracy over the full spectrometer range.

The algorithm used here is based on a numerical comparison of theoretically calculated Fabry-Perot peak positions with the measured ones. The strength of the algorithm is that it has a unique solution as shown in Figure 2 above.

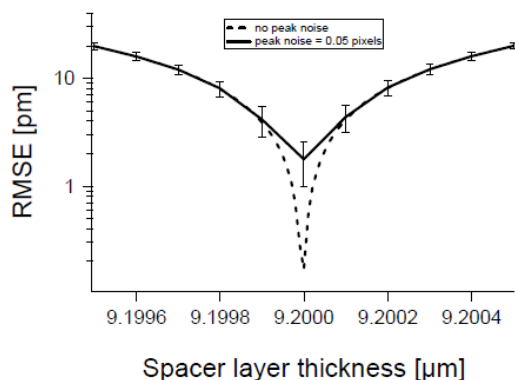


Figure 2. Uniqueness of the algorithm solution shown as a single minimum of the fitting argument RMSE (=spectral root mean square error).

As a side product of this calculation, we obtain the Fabry-Perot spacer layer thickness. If this thickness is accurately determined beforehand, and, a rough calibration of the spectrometer is known, the high accuracy calibration can proceed even without the use of a Hg calibration lamp.

3. ABOUT THE ACCURACY ACHIEVED

The strength of HICALOS lies in its stable high accuracy over the full spectral range. Particularly in wavelength ranges distant from Hg/Ag calibration lines the accuracy is enhanced by a factor of 2x-10x compared to any conventional methods.

The presented method is of particular use to account for the non-linear nature of modern miniature spectrometers, which are currently not used in high accuracy operation, or, to detect small non-linearities that are due to otherwise undetected grating imperfections. See also Figure 3 below for an example.

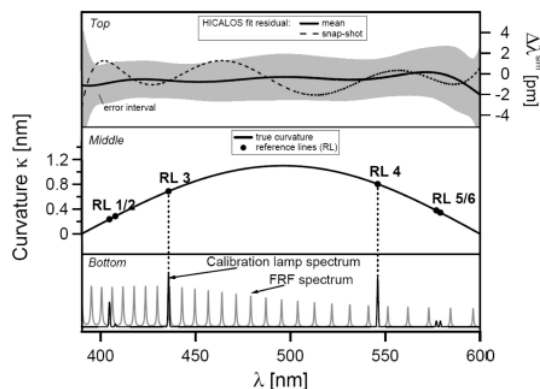


Figure 3. Determination of miniature spectrometer non-linearity between 380nm and 600nm at only a few picometer accuracy. The undulation of the calibration function in the top part (error plot) is related to the use of a polynomial form in this example. The calibration lamp reference lines (RL) are shown in the middle part. Only two were actually used for the iterative calibration algorithm.

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PRACTICAL METHOD FOR BANDPASS AND STRAY LIGHT CORRECTION OF ARRAY-SPECTRORADIOMETER DATA

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ABSTRACT

A practical matrix inversion-based method for a simultaneous correction of both bandpass and stray light effects in the measurement data of array spectroradiometers is presented. For this purpose, an instrument matrix filled with line spread functions is determined with the help of tuneable lasers. Subsequently applying an established matrix regularization technique, a straightforward deconvolution of the measurement results is possible.

Keywords: Bandpass, slit function, stray light, matrix inversion, deconvolution, spectroradiometer.

1. INTRODUCTION

With the advent and progress of SSL technologies, spectral characterization of the new type of light sources has become an inseparable part of their photometric and colorimetric assessment. This task is especially facilitated by the availability of compact, fast, cost-efficient and easy-to-handle CCD-array spectroradiometers. However, these devices are far from being perfect in terms of their spectral transfer (response) functions, i.e. they have a finite bandpass and also a non-zero response in the out-of-band range. Hence, both the bandpass and the stray light corrections often need to be applied to the measurement data. Such a correction is commonly known as spectral deconvolution. Unfortunately, a direct deconvolution of measured spectra faces the well-known problems related to the stability of the solutions. Therefore, existing correction techniques typically deal separately with either the bandpass [1-4] or the stray light correction [5-6]. In this contribution, we present a matrix inversion-based method that makes possible a simultaneous correction of both the bandpass and the stray light effects.

2. MATRIX METHOD FOR COMPLETE SPECTRAL CORRECTION OF SPECTRORADIOMETER DATA

Similar to the method of spectral stray-light correction by Zong et al. [6], the prerequisite for the spectral corrections is the knowledge of instrument functions (line spread functions) for every pixel of an array spectroradiometer. In practice, however, it is often possible to shorten a tedious tuneable laser-based characterisation procedure by interpolation of the line spread functions determined only at a limited number of monochromatic laser wavelengths. For a CCD array spectroradiometer, the instrument functions can be expressed as a square matrix and the measured spectrum X is described in terms of matrix multiplication

$$X = AY \quad (1)$$

where A denotes the instrument matrix and Y the vector of the true spectrum. Thus, a correction for the instrument function may be achieved by the inversion of (1). However, for array spectroradiometers the instrument matrix A is typically ill-conditioned. Therefore, the direct solution of (1) by the matrix inversion yields results which are unstable with respect to small perturbations of the measured spectrum as well as perturbations of the estimated instrument matrix. In order to achieve a stable solution of (1), regularization techniques can be applied. We propose to apply the Tikhonov regularization [7] for the solution of (1) by minimizing

$$\|AY - X\| + \|\Gamma Y\| \quad (2)$$

where $\|\cdot\|$ is the Euclidian norm and Γ denotes a suitably chosen regularization matrix. Here $\Gamma = \alpha I$ is used where I is the identity matrix. The regularization parameter α is usually chosen from a trade off between a small residual norm ($\|AY - X\|$) resulting from a small value of α and a small norm of the solution Y , which is achieved for large α . This approach is also followed when applying the L-curve criterion

for finding α [7]. In practical terms, too small a value of α yields “noisy” results, too large a value results in a biased correction. For the Tikhonov regularization, the approximate solution of (1) is given by

$$Y_{\alpha} = (A^T A + \alpha I)^{-1} A^T X$$

that is, the matrix $(A^T A + \alpha I)^{-1} A^T$ can be used as a spectral correction matrix.

Note that the method proposed by Zong et al., where the bandpass region surrounding the main diagonal of the instrument matrix is set to zero, also results in a regularization of the instrument matrix. However, there the bandpass region of the instrument function is mainly discarded and, hence, bandpass effects are not corrected. In contrast, when applying the Tikhonov regularization (3), the full instrument matrix A is taken into account. Therefore, the proposed method simultaneously corrects for stray light as well as bandpass effects covered by the instrument function.

3. DETERMINATION OF INSTRUMENT MATRIX

For the determination of the instrument matrices A of array spectroradiometers, required for the spectral corrections, we use the Pulsed Laser for Advanced Characterisation of Spectroradiometers (PLACOS) setup at PTB [8]. The PLACOS setup (see Fig.1) includes a solid-state laser system generating 5 ns pulses at a repetition rate of 20 Hz. Use of optical parametric oscillator accompanied by a second harmonic generator enables a straightforward automated selection of laser wavelengths within the spectral range from 220 nm to 2200 nm (Fig. 2). Despite the pulsed mode of operation of the laser system, the relative measurements of line spread functions (LSF) of array spectroradiometers yield results equivalent to those obtained using a cw-laser system. The equivalence of the characterisation results has been proved by comparing instrument matrices determined at the PLACOS setup and at the purely cw-laser facility TULIP of PTB [9]. The acquisition, maintenance and operative costs of such a compact pulsed laser system, however, are significantly lower than those of an equivalent cw laser system covering the same spectral range and, thus, making it attractive also for a wider range of users.

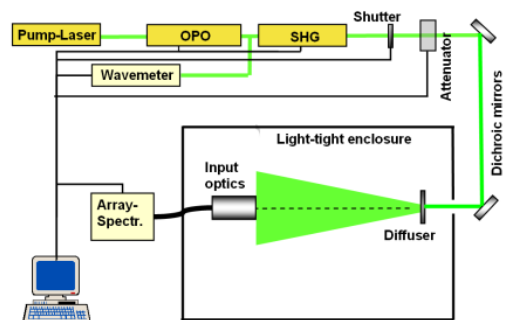


Figure 1. PLACOS setup: OPO, optical parametric oscillator; SHG, second harmonic generator.

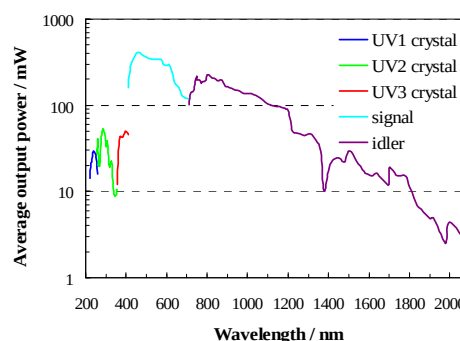


Figure 2. Average output power of the PLACOS setup. At wavelengths between 410 nm and 2200 nm the signal and idler waves of the OPO are used. The radiation at shorter wavelengths is provided by the SHG unit with different crystals.

Figure 3 shows the measured response of a CCD-array spectroradiometer to the laser radiation at several representative wavelengths. As can be seen from the Figure 3, the LSFs of the device have rather high interreflections-caused shoulders to the left of the bandpass region. The stray light level ranges from a few parts in 10^3 in the vicinity of the bandpass peak to a few parts in 10^5 at the far end from the excitation wavelengths. Figure 4 shows that the full-width-half-maximum (FWHM) of the bandpass function is not constant over the spectral range of the instrument. Moreover, the shape and the symmetry of the bandpass function are also noticeably varying with wavelength, which would have an effect on e.g. the colorimetric characterisation results of LEDs. Hence, both bandpass and stray light correction are needed for the measurement results using the instrument.

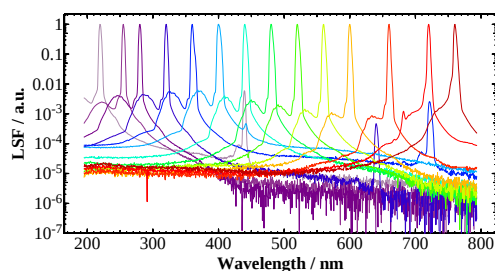


Figure 3. Line spread function of a CCD array spectroradiometer for a number of excitation wavelengths shown on a logarithmic scale.

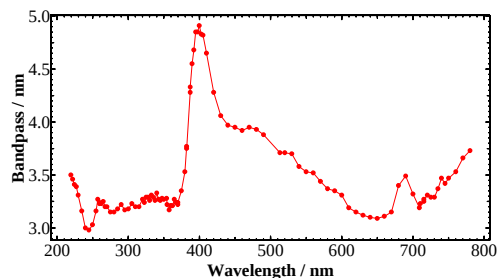


Figure 4. Bandpass (FWHM) variation of the array spectroradiometer as a function of wavelength.

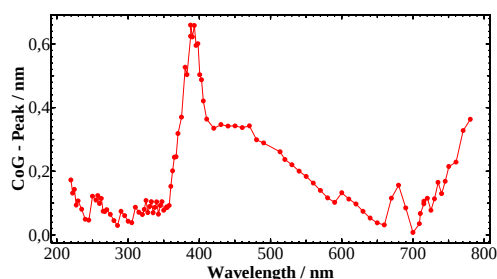


Figure 5. Difference between the centre-of-gravity and the peak wavelengths of the spectroradiometer determined from the bandpass functions over the entire spectral range of the instrument. The difference provides an indication on the symmetry of the bandpass functions and have to be considered during wavelength scale calibration of the spectroradiometer.

4. METHOD VERIFICATION ON LED DATA

The performance of the method for the simultaneous bandpass and stray light correction was tested with several CCD-array spectroradiometers in LED measurement applications. Figures 6, 7, and 8 demonstrate the effectiveness of the spectral corrections applied to the spectral power distribution of blue, green and red LEDs, respectively, measured by the array spectroradiometer (for the spectral characteristics of the device see Figures 3, 4 and 5). The bandpass and stray light

correction of the three LED measurement data is achieved by one correction matrix determined with the help of Tikhonov regularisation technique. For the matrix inversion operation yielding a stable solution, a single-number regularisation parameter α was enough. Comparison of the results of the corrections shows that the full spectral deconvolution method based on instrument matrix inversion with the help of Tikhonov regularisation technique is capable of carrying out the task of simultaneous correction of both the bandpass and the stray light effects. As can be seen from the results in Table 1, the spectral corrections have a noticeable effect on the determined colorimetric parameter of the LEDs.

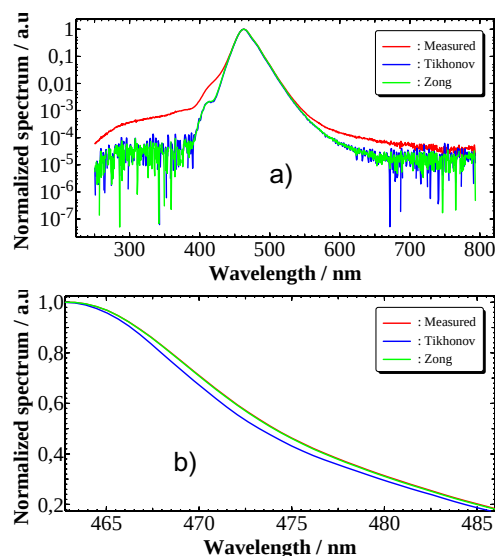
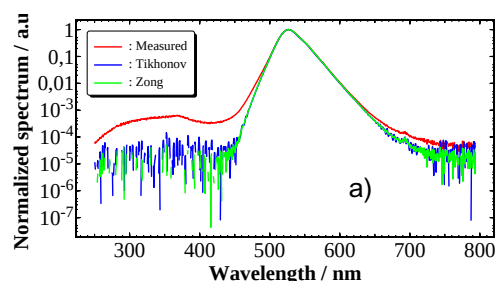


Figure 6. Spectral power distribution of a blue LED: a) a measurement result of a CCD-array spectroradiometer, a result of the complete spectral correction by applying the Tikhonov matrix regularisation method, and a result of the stray light correction by the method of Zong et al.; b) close up on the bandpass region.



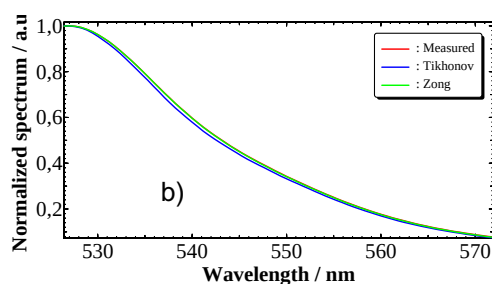


Figure 7. Spectral power distribution of a green LED: a) measured as well as corrected data shown on a logarithmic scale; b) close up on the bandpass region.

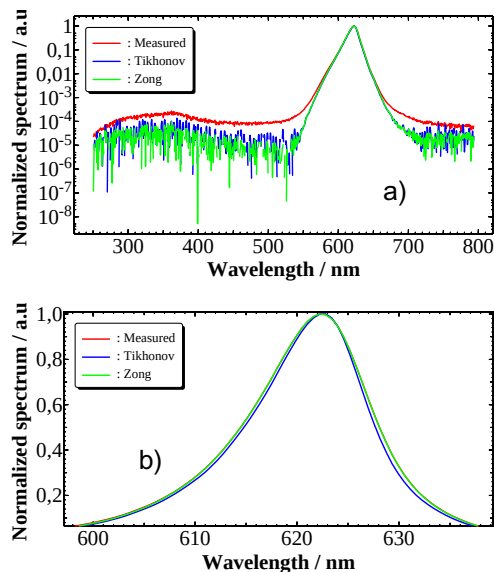


Figure 8. Spectral power distribution of a red LED: a) measured as well as corrected data shown on a logarithmic scale; b) close up on the bandpass region.

Table 1. Bandpass (FWHM) and chromaticity coordinates (x and y) of the LEDs and their change as a result of the simultaneous bandpass and stray light correction (Tikhonov) as well as just the stray light correction (Zong).

LED	Data	FWH M, nm	Δx	Δy
Blue	Measured	20.83	0.135	0.0550
	Tikhonov	-1.03	-0.0001	0.0009
	Zong	-0.09	-0.0005	0.0001
Green	Measured	29.25	0.2055	0.7355
	Tikhonov	-0.68	-0.0012	0.0047
	Zong	-0.13	0.0002	0.0037
Red	Measured	13.63	0.6804	0.3190
	Tikhonov	-0.72	0.0013	0.0009
	Zong	-0.02	0.0013	0.0009

5. CONCLUSIONS

Full spectral deconvolution resulting in a simultaneous correction of both bandpass and stray light effects is possible by means of instrument matrix inversion. Tikhonov regularisation method can be successfully applied for the instrument matrix inversion to yield a stable result. At least for the use with LED data, the regularisation parameter can be found in a straightforward way. As a result, a matrix for complete spectral correction can be determined for practical use with the instrument data.

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