Characterizing Ultraviolet Germicidal Irradiance Luminaires†

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ABSTRACT

In upper-room ultraviolet germicidal irradiance (UVGI) design, irradiance is an important characteristic, with two opposing dominant dynamics: high-level irradiation on the microorganism and minimum levels of irradiance on human skin and eyes. The use of high-level ray-tracing procedures is followed in establishing radiance and irradiance levels. The main constants in a room influencing these calculations are the spectral and spatial characteristics of the radiation sources in the inter-reflecting surfaces inside the luminaire, as well as the surfaces in the room. The most important characteristic to be determined for the radiation source prior to calculations is its spatial radiant intensity distribution. This characterization is performed using a gonioradiometer. The complexity of the physical construction of the luminaire will determine the extent to which measurements have to be taken. Accurate gonioradiometer readings provide the required radiant intensities in all directions for computer-aided design (CAD), and can also be used to determine the total radiant flux leaving the luminaire, as well as calculating isoirradiance surfaces around the UVGI luminaire. This study will present a laboratory experimental approach to deriving the radiant intensity distribution of a UVGI luminaire. The UVGI luminaire is then characterized *in situ*, and compared with the gonioradiometric output.

INTRODUCTION

The design of the illumination of buildings for building esthetics and functionality requires comprehensive data of luminaires, to be used in visual and lighting software. It is therefore standard practice to characterize luminaires in a laboratory by gonioradiometry. Similarly, it would be beneficial to characterize upper-room upper-room ultraviolet germicidal irradiation (UVGI) luminaires, however, the dynamics of upper-room UVGI is different, and consequently the characterization of these luminaires by gonioradiometry would be different. UVGI is the use of ultraviolet (UV) light in the germicidal range (200–320 nm) for the disinfection of air or surfaces (1). Upper-room UVGI luminaires typically incorporate louvers across lamps to collimate the UV beam. This results in high-level irradiation on the microorganism in a defined (designed) zone, and minimum levels of irradiance on human skin and eyes to reduce the UV exposure in the lower, occupied zone of the room. Zhang *et al.* (2) developed a protocol for the gonioradiometry of upper-room UVGI luminaires based on standard photometry methods. Their experimental set-up used a moving-mirror Type-C gonioradiometer. Their output data was in the form of general fluorescent luminaire data as IES files. Files of this form are used in lighting and visual software.

In this paper, a UVGI luminaire is characterized by gonioradiometry. The luminaire is then characterized *in situ* and the characterizations by both procedures are compared.

MATERIALS AND METHODS

Materials. In this study, a Lumalier (WM-136 with two lamps) wall-mounted luminaire shown in Fig. 1 is characterized using a gonioradiometer and *in situ*. The luminaire has dimensions of 510 mm × 210 mm × 130 mm. It comprises 14 louvers, eight of these louvers are black, and six are made of a reflective material. Two Philips PL-L36WTUV lamps (Roosendaal, The Netherlands) are positioned behind the louvers in front of a flat reflective sheet. According to Lumalier WM-136 (Lumalier Surface and Air Disinfection, Memphis, TN, USA) ordering information (3) one 36 W lamp produces 12 UV-C W. UV rays may leave through the front and sides of the fixture.

Gonioradiometry. The radiant intensity distribution for the luminaire is characterized using a gonioradiometer. The gonioradiometer is located at the University of Pretoria's Radiometry and Photometry Laboratory, and is of Type C, *i.e.*, stationary luminaire and rotating sensor, and is shown in Fig. 2.

The gonioradiometer was designed at the University of Pretoria under a series of undergraduate projects. The laboratory is painted matte black to minimize the reflectivity of rays. Because of limited space, the gonioradiometer does not include a mirror to achieve additional distance from source to detector. In-house developed shaft encoding (*via* MATLAB) and control systems produced a system with a resolution and repeatability of 0.0174°, which is approximately 2 min of arc. The distance between the source and detector is 2.65 m, therefore practical testing is limited to small sources having a radiating length of approximately 300 mm. A wide dynamic range of radiant intensities were measured, and the use of UVGI detector/filter/amplifier combination in a discrete package was essential. A Goldilux UV-C (200–280 nm) photodetector, coupled with a 1000 MÙ feedback resistor, measured the radiant intensity of the luminaire at predetermined positions. Changes in voltage were measured, and correlated with radiant power. The gonioradiometer was automated to perform a set of vertical angular measurements. It was not automated to perform horizontal measurements, and the luminaire was manually positioned for varying horizontal planes.

The protocol used in this exercise follows that developed by Zhang *et al.* (2). It comprises 65 vertical angles, for 23 horizontal planes, a total of 1495 measuring points per luminaire. These measuring points will characterize half the irradiance spectrum of a wall-mounted fixture. The full spectrum is completed under the assumption that the luminaire is symmetric in design. These angles are shown in Tables 1 and 2. It is

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Figure 1. The luminaire characterized in this project.

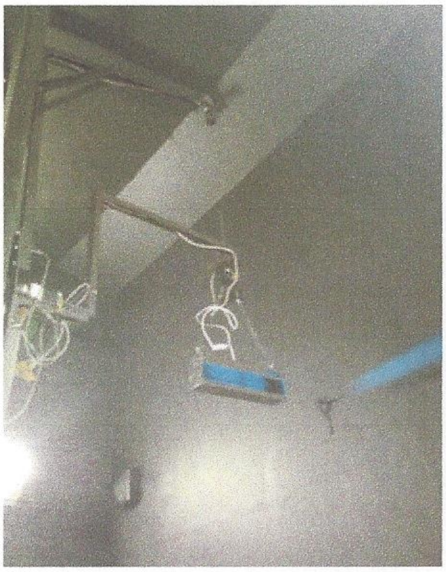

Figure 2. Gonioradiometer used to characterize UVGI luminaires.

Table 1. Vertical angular measuring points.

Range	Increment
0°	–
5°–35°	10°
42.5°–52.5°	5°
57°–61°	4°
64.5°–70.5°	3°
73°–81°	2°
82°–84°	1°
84.5°–96°	0.5°
97°–99°	1°
101°–107°	2°
109.5°–115.5°	3°
119°–123°	4°
127.5°–137.5°	5°
145°–175°	10°
180°	–

anticipated that the maximum irradiance will peak near 90° vertical angle, and toward either end of the vertical array, *i.e.* 0° and 180°, the irradiance will tend toward zero.

The laboratory was set to 22°C ± 2°C throughout the gonioradiometric characterization. The luminaire was switched on 12 h prior to commencement of the characterization, and remained on for the entire characterization.

In situ characterization. The *in situ* characterization was performed at the Witbank Airborne Infection Research facility. Five Lumalier WM-136 (two lamps) wall-mounted luminaires had been installed in this facility; three are characterized here. The luminaires were located in patient rooms and a corridor between patient rooms. The aim of the *in situ* characterization tests was to determine the irradiance distribution of the luminaires, taking room effects into account. This exercise involved measuring the irradiance in the horizontal and vertical directions, according to protocols developed at the Harvard School of Public Health (Hunt, D and Linnes, J, personal communication).

Horizontal angular measurements are performed according to the convention presented in Fig. 3. The midpoint of the luminaire is illustrated in Fig. 3. All angles to the right-hand side of this point are negative, and all angles to the left-hand side are positive. The range of horizontal angular measurements is limited by the floor area of the room, and hence, the hori-

Table 2. Horizontal angular measuring points.

Range	Increment
0°	–
1°–17°	2°
19.5°–25.5°	3°
29°	–
33.5°–37.5°	4°
42.5°–47.5°	5°
55°–85°	10°
90°	–

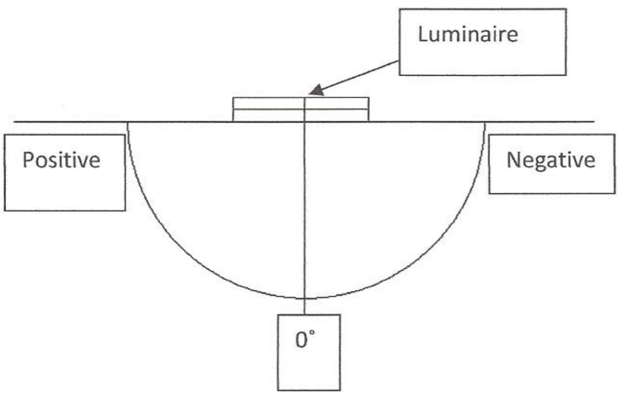

Figure 3. Convention for horizontal (*in situ*) angular measurements.

zontal angular range for each of the three luminaires differs, as reported in Table 3.

In all patient rooms, the luminaire was mounted near a corner so that one quadrant (either positive or negative) was limited to only a few measurements, whereas the other quadrant had significantly more readings. All horizontal angular measurements are recorded at a distance of 1.5 m away from the face of the luminaire. The convention for establishing negative and positive vertical angles is similar to that of the horizontal angles. The 0° point is assigned at the vertical height of the midpoint of the luminaire. The negative angles are above this point, and the positive angles below this point. The corresponding angular heights of the Lumalier luminaires are shown in Table 4. The vertical angular measurements were measured at the 0° horizontal point, 1.5 m away from the face of the luminaire.

A Goldilux UV-C meter (Model number: GUVCP-1L), mounted to a drip stand, was used to measure the irradiance of the luminaires. The sensor was positioned with a laser, to always be pointing to the center of the luminaire. The lamps used in the gonioradiometric characterization of the luminaire had been removed from one of the luminaires of the research facility. In this way, the lamp had an almost identical life cycle as those characterized *in situ*.

RESULTS

Gonioradiometry results

Table 3. Range of horizontal angular measurements for the UVGI luminaires.

Room	Range
Corridor	−20° to 30°
Ward C1	−5° to 75°
Ward C3	0° to 75°

Table 4. Vertical heights for vertical angular measurements of the UVGI fixtures.

Angle	Height (m)
−5°	2.40
0°	2.25
5°	2.10
10°	1.95
15°	1.79
20°	1.62

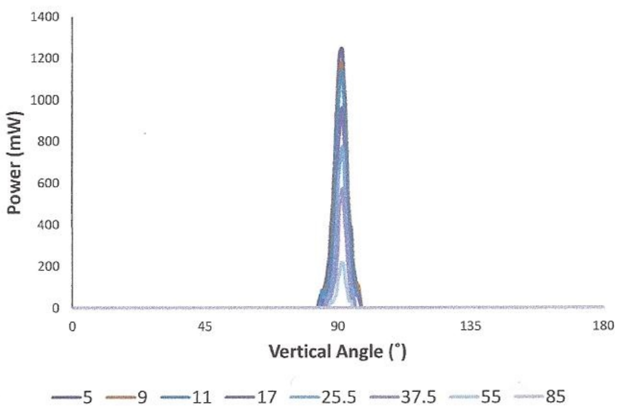

Figure 4. Vertical angular power distribution at various horizontal planes.

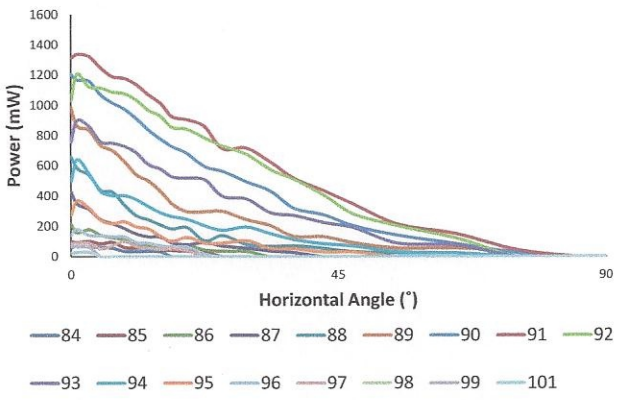

Figure 5. Horizontal angular power distribution at various vertical angles.

In the gonioradiometric characterization of the luminaire, the radiant intensity distributions are presented, in Figs. 4 and 5, as a power output of the UV energy leaving the luminaire. The vertical angular radiant intensity distribution in different horizontal planes is shown in Fig. 4. Radiant intensity levels were only recorded in a narrow band between 84° and 101° levels were highest near the 0° horizontal plane, and decreased as the horizontal plane tended toward 90°. In the 85° degree horizontal plane, radiant intensity levels were too low to be measured.

As radiant intensity levels were only recorded in the 84°–101° vertical bands, the horizontal angular radiant intensity distribution of this band is presented for discussion, in Fig. 5. In each vertical angular distribution, the UV energy peaks at a 0° horizontal angle and decreases as the horizontal angle tends toward 90°. In the vertical angular distributions, the radiant intensity levels increase from 84° to 91°, and decreases from 92° to 101°.

In situ characterization results

In situ characterization was performed with a Goldilux (Model number: GUVCP-1L), UV-C meter, and the output was recorded as irradiance measured in $\mu W/cm^2$, as presented in Figs. 6 and 7. The vertical angular measurements of the luminaire are shown in Fig. 6. Only a single measurement (−5°) is made above the horizontal, as this range is limited by the ceiling height. At 10° below the horizontal, at a height of 1.95 m, the irradiance is already as low as 0.2 $\mu W/cm^2$. At eye level, both fixtures have

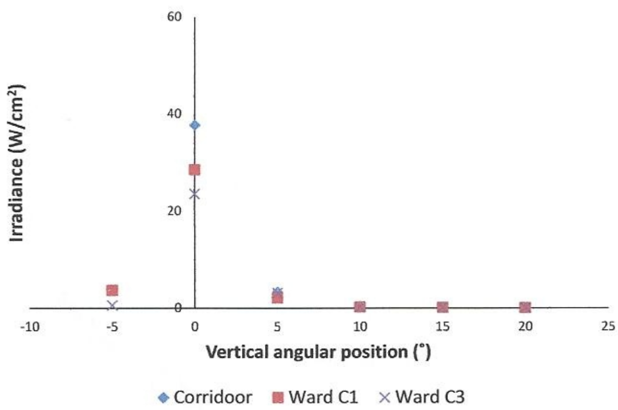

Figure 6. Vertical angular *in situ* characterization of the luminaire.

irradiance levels below the threshold limit value set by the CIE of 0.2 $\mu W/cm^2$ (4).

The horizontal angular characterization is presented in Fig. 7. In Wards C1 and C3, a curtain rail is located close to the luminaire. This caused omission of some readings, as the experimental set-up collided with the curtain rail. These measurements are the 5° readings in Wards C1 and C3. The results show that the luminaire in the corridor, Wards C1 and C3 display a similar trend, however, there is greater variation in readings. There is an initially gradual decrease in measured irradiance moving away from the midpoint, followed by a steeper decrease in measured irradiance. The lowest measured irradiance is in Ward C3, recording 5.8 $\mu W/cm^2$ at 75°.

A comparison between the gonioradiometric and *in situ* characterization of the luminaire is presented in Figs. 8 and 9. The *in situ* vertical angular range, as presented in Fig. 8, is adjusted from −5° to 20° to align with the gonioradiometric range 85°–110°. The mean *in situ* data are the mean irradiance from the corridor, and Wards C1 and C3. In the vertical angular range, the gonioradiometric irradiance peak, near 90°, is greater than that of the mean *in situ* irradiance. The trend in both characterizations is similar, tapering toward 0° in a very narrow band.

The *in situ* horizontal angular range, presented in Fig. 9, depicts different trends between the gonioradiometric and *in situ* characterization of the luminaire. In the *in situ* characterization, the irradiance gradually drops off from 0°. In the gonioradiometric characterization, the irradiance drops off steeply as the horizontal angle increases from 0° to 90°.

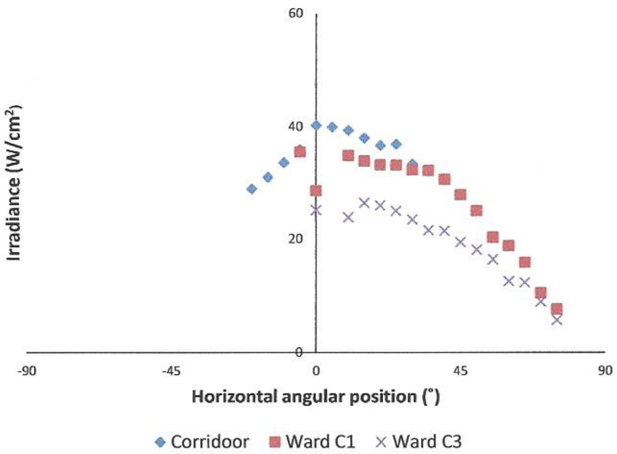

Figure 7. Horizontal angular *in situ* characterization of the luminaire.

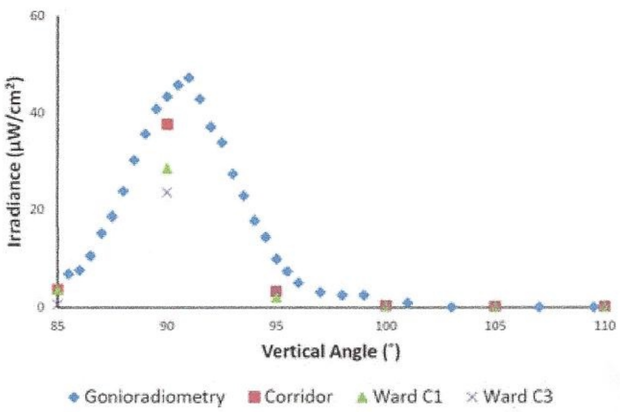

Figure 8. Comparison between gonioradiometry and *in situ* characterization (vertical angular range).

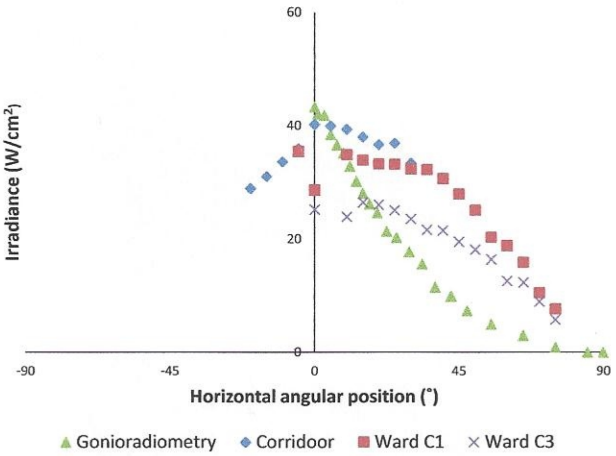

Figure 9. Comparison between gonioradiometry and *in situ* characterization (horizontal angular range).

DISCUSSION AND CONCLUSION

There is a significant difference in irradiance distributions between the gonioradiometric characterization and *in situ* characterization of the luminaire. At the midpoint of the luminaire, the gonioradiometric irradiance at 1.5 m is calculated as 43.30 $\mu W/cm^2$. The corresponding measurement in the *in situ* characterization varies from 25.19 $\mu W/cm^2$ in Ward C3 to 40.22 $\mu W/cm^2$ in the corridor, a variation of between 41.8% and 7.1% between gonioradiometric and *in situ* characterizations. While the differences in irradiance in the *in situ* characterization could be attributed to the inherent difference which may exist in different luminaires of the same design, the same general trend was still present in the *in situ* characterization of luminaires in Wards C1 and C3, and corridor. A comparison of the vertical angular array of the gonioradiometric and *in situ* characterization (Fig. 8) shows a similar trend, however, the gonioradiometric characterization peaks much higher than the mean *in situ* characterization. A comparison of the horizontal angular array of the *in situ* and gonioradiometric characterizations (Fig. 9) reveals different irradiance profiles. The gradual decrease in irradiance in the *in situ* characterization *vs* the steep decrease in irradiance in the gonioradiometric characterization, moving from 0° to 90°, may indicate that the reflective properties of the walls and other finishings increase the irradiance that would be incident upon a receiver. This reflectivity would be absent in the photometry lab in which the gonioradiometric characterization was performed. Reflectivity thus becomes an important consideration for installation design, including CAD software, as the interaction between UV rays leaving luminaires and the surfaces in the room, *i.e.* walls and ceilings, may enhance the irradiance levels in the (upper) room. This also becomes an important consideration in the lower room, where irradiance levels should be kept to below the threshold limit value. The reflectivity of UV by different materials has been previously investigated, and is reported in Kowalski (1) and Philips (5).

While no formalized method for the characterization of UVGI luminaires has been accepted into common practice, the steps taken by Zhang *et al.* (1) provide a comprehensive basis for laboratory characterization of these luminaires. In this study, with its current gonioradiometric set-up, the characterization was performed over a period of almost 2 weeks, which becomes an expensive process. The data gathered from this characterization show large areas of the characterized quadrant which have zero UV value. This area corresponds largely to the area outside the collimated UV beams. The protocol could be refined to address this, which could result in a lower number of readings, without reducing the integrity of the data within the collimated region. In addition, *in situ* characterization is also not a formalized process. The protocol followed in this study aimed to develop a three-dimensional profile of luminaire in a room. This method is useful in determining the interaction of UV with surfaces in the room. It is, however, coarse and limited to a defined volume, or sphere, and characterization beyond this point is an extrapolation, at best. The method requires further investigation, and possibly refinement, in both the upper and lower room.

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