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Critical assessment of optical sensor parameters for the measurement of ultraviolet LED lamps

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ABSTRACT

Measurement of light output from ultraviolet (UV) light-based devices is critical to understanding the capability of the device. Optical sensors such as radiometers and dosimeters can possess different angular responses and are sensitive to many parameters in the measurement set-up. This work has been designed to quantify the effect of multiple parameters on the measurements obtained from optical sensors to provide inputs for validating measured data for ultraviolet sources. Multiple light sources operating in the ultraviolet range have been measured and a comparison between different sensors is presented. The angular response has been evaluated for each detector and compared with an ideal cosine response. Two of the six sensors studied displayed a near cosine response. A change of angle of acceptance with wavelength was observed for the ThorLabs S120VC and ILT W Optic diffuser. Due to use of artificial heating, the effect of measured intensities on the sensor as a function of temperature was seen to be insignificant but provided an understanding of how temperature of the sensor can influence measured data. Finally, the effect of ambient light and the integration time on the measured data were investigated. The effect of ambient light proved to be significant, when not considered in measurement of low light signals sources while the effect of choosing an ideal integration time has been seen to impact the measurements obtained. A measured difference of 43% was observed between a saturated and unsaturated sensor.

1. Introduction

Ultraviolet light has a wide variety of applications in industry, including disinfection [1], lighting [2], photocatalysis, UV paint curing and UV glue curing [3,4]. The recent coronavirus outbreak has led to increased interest in finding solutions using ultraviolet light, specifically in the UV-C wavelength ranges (240 nm – 280 nm [1]), to achieve effective disinfection of surfaces and air. As of 2021, the shortest wavelength UV LEDs produced and available commercially is 230 nm [5].

Increased interest in UV-C LEDs has developed the need for a better understanding of light measurement techniques. Sholtes et al. explored the development of a comparison protocol between measurements done using devices from different manufacturers [6]. Radiometry is the science and technology of measuring and quantifying electromagnetic radiant energy. Two commonly used terms in radiometry are intensity (or radiance) and flux (or irradiance) [7,8,9].

Grum et al. [10] established different configurations of radiometric measurement systems, one of which can be seen in Fig. 1(a). A typical light measurement system consists of a light source, transmission medium, and a sensor or detector that, when exposed to light, generates current or voltage proportional to the amount of light received. The signal processor then converts the incoming signal to a light-level reading in units such as watts, watts per square centimeter, etc. The measurements systems can be configured with different optics to suit the set-up for a particular measurement [8,10]. The light source is the main component of interest in these measurements. If the source is small in the context of the measurement to be conducted, the source approximates to a point source. However, in practical applications, all light sources are extended sources. Extended sources are sources where the size of the source is larger than the capability of the measurement system. If the system emission angle is higher than the acceptance angle of the detector, measurements taken will be lower than the actual light emitted by the source and hence not completely valid for further use

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unless the loss is factored in. Measurements will be valid only when done at long working distances so as to capture most of the light emitted (Fig. 1(b)) [11]. The lighting industry also employs integration spheres for light measurement although there are very few integrating spheres in the market that can be used for ultraviolet sources due to the effect of ultraviolet light on the inner coatings of the integrating sphere. For industrial light systems and scientific experiments, where the light source consists of multiple LEDs running in series or parallel combinations, the concept of extended source is essential for the accurate measurement of light intensity. Different light measurement techniques are used by light system manufacturers and scientific experts to understand the behavior of light at a given point of interest including chemical actinometry, radiometry/dosimetry, optical modelling and discrete ordinate modelling [2].

In radiometry, a detector/sensor plays a vital role in ensuring measurements are valid and acceptable. Every detector head has a light receiving surface where the light enters the detector head, a detector where the light from the source falls onto and a cable that transmits the light received to be recorded by the sensor [12]. Most detectors are silicon photodiodes or CCD based multi-channel array detectors, which are very versatile and reliable. A detector's spectral sensitivity is equal to the product of its responsivity and the transmission of the coupling optics within it [13]. An ideal detector measuring a light source would have a cosine response. A perfect cosine response is one where the device agrees with lamberts cosine law [14]. A device that has a cosine response is a Lambertian receiver [15]. As shown in Fig. 1(a), while the set-up used to measure the light source can be simple, it is necessary to know if the measured values are valid and can be used for further calculations. For example, research has shown the variability of measurements done by equipment from different manufacturers [6].

Despite extensive research on measurement techniques, characterization for UV LED measurements [1,6], there is a need for understanding the data obtained from the measurements and exploring the validity of these measurements. Questions associated with standard protocols used in radiometric measurement have been explored [6,16] but possible effects of errors in measurement have not been quantified. While there are many books and papers on optical and light measurements [2,6–11,13], there is a need to establish common errors, such as placement of detector with respect to the light source, temperature of the sensor etc., that operators may induce, unknowingly, while measuring extended light sources. The goal of this paper was to quantify the variability in measurement of LED lamps centered in the UV range of light spectrum as affected by equipment used. The paper further compares sensors that operate in the wavelength range of 265 nm – 395 nm of UV and discusses the importance of understanding the compatibility of the sensor for the measurements to be recorded.

2. Materials and methods

2.1. Sensors

While meters can have the same form factor, there can be a wide range of specifications that can differ between each manufacturer. For example, one of the principal differences between meters is the calibrated wavelength range of the meter and their planar sizes. It is necessary to evaluate each measurement set-up on a case-by-case basis and to choose a meter that encompasses the range of measurements required for the specific application.

Table 1 lists sensors from four different manufacturers used in this study. Fig. 2 depicts the calibrated wavelength measurement ranges of each detector head and optic when the entire area of the detector head or coupling optic is evenly illuminated. These values are based on the parameters provided by the manufacturer in their datasheets.

Loctite dosimeters are built to measure narrow-band wavelengths, specifically for LED light curing devices. The meter has a screen display where the data and profile can be read [18,19]. ThorLabs S120VC has typical applications for low power lasers and LEDs. The sensor uses a large active area combined with a reflective, diffused filter. Data measured using the ThorLabs sensor can be downloaded and accessed for further analysis [20]. Ophir sensors have diffusers that suppress out-of-band light. The meter has a built-in display and memory capacity that can be downloaded onto a computer for further analysis [21]. International Light Technologies (ILT) manufactured sensors are portable spectroradiometers with a wide range of calibrated wavelengths. These meters use a coupling optic that receives and transmits data to the

Table 1
Sensor Specifications.

Detector Head	Manufacturer	Meter	Intensity Range	Aperture Diameter (mm)
UV A/B 1390323 [18]	Loctite	UVA/B Radiometer Dosimeter	5 mW cm^{-2} –20 W cm^{-2}	0.75
UV V 1265282 [19]	Loctite	UV-V Radiometer Dosimeter	5 mW cm^{-2} –20 W cm^{-2}	0.75
S120VC [20]	ThorLabs	PM100D Radiometer	70 nW cm^{-2} –70 mW cm^{-2}	9.5
PD300RM-8 W [21]	Ophir	Starbright 7,201,580 Radiometer Dosimeter	1 μW cm^{-2} –8 W cm^{-2}	8
RAA4 Right Angle Cosine adapter [23] **	International Light Technologies (ILT) [22]	ILT950UV Spectro-radiometer	1 nW cm^{-2} – 100 mW cm^{-2}*	6.9
W Optic Diffuser [23] **	International Light Technologies (ILT) [22]	ILT950UV Spectro-radiometer	1 nW cm^{-2} – 100 mW cm^{-2}*	24

[*] No specific information on the datasheet, range based on measurements done with SpectrILite software.

[**] RAA4 and W components from ILT are coupling optics and not detector heads [23].

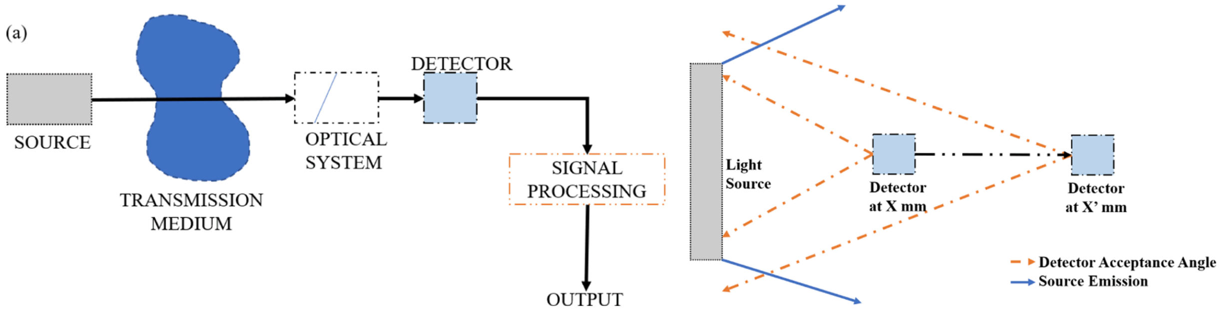


Fig. 1. (a) Typical configuration of radiometric measurement systems adapted from [10], (b) Schematic representation of an extended light source.

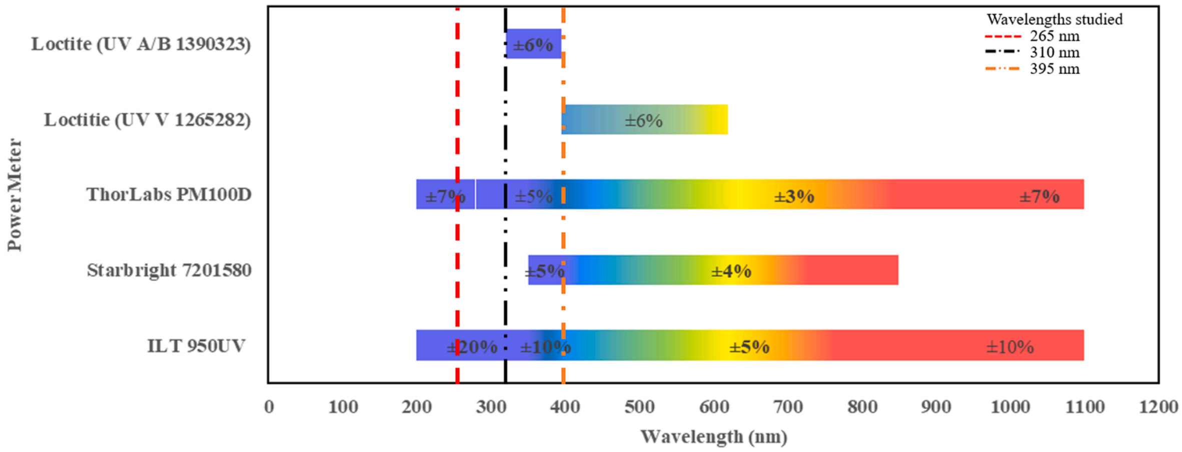


Fig. 2. Peak wavelength of light sources studied (dotted line),wavelength range and intensity calibration accuracy of the sensors used. Own elaboration based on manufacturers data [18–22].

detector array inside the ILT spectroradiometer. The data measured by the coupling optic can be read on the software provided by the manufacturer, SpectrILite III [22]. The Loctite, ThorLabs and Ophir based sensors employ a console for data measurement and storage while the ILT based spectroradiometer employs a software layer meter head that supports user based light measurement.

2.2. Sources – Light emitting diodes

Three light sources of different spectral emission in the UV-A, UV-B and UV-C ranges were analyzed. The LEDs chosen for this work were 265 nm (KL265-50U-SM-WD, Klaran), 310 nm (EOLS-310–697, EpiGap) and 395 nm (CUN96A1B, Seoul-SeTi). To conduct experiments, the LEDs were solder attached to starboards (601019.01, 60050, Lumitronix).

Spectral measurements were made to ensure that the emission of the chosen LEDs was centered at the wavelengths of interest and measured using the ILT spectroradiometer with the RAA4 coupling optic (2003357U1, ILT). Fig. 3 shows the spectrum of each LED relative to their peak wavelength.

2.3. Set-up for experiments

The LED soldered onto a starboard substrate were mounted to a heatsink for cooling (as shown in Fig. 4 (a)).

2.3.1. Angle of acceptance

The angle of acceptance is defined as the maximum incident angle at which an optical element (lens, fiber) will transmit light that can be detected and measured by the detector [8]. To measure the maximum incident angle for each of the detector/coupling optics used in this study, a rotating fixture was used; see Fig. 4(b). The detector head is coaxial to the source. The light source selected is a single point source, which means that the amount of light measured is lower than the range of the detector manufactured by Loctite (minimum of 5 mW cm^{-2} required). For Loctite detectors, a lens (Fresnel Tech #0.3) was used in front of the source to increase signal strength reaching the detector. Refer to additional data for the change in the set-up for the Loctite detectors (Figure S5). For the purpose of this paper, angles between 0° and 180° were studied in steps of 10°. A working distance of 100 ± 0.1 mm was maintained between the light source and aperture. Three replicate measurements were taken on separate days to ensure that measured data were repeatable and reproducible for each detector used in this study. For further information on the set-up and rotating fixture, refer to additional data (Figures S1 – S5).

2.3.2. Ambient and stray light

Ambient light is all the light present in the room before switching the light source “ON”. In some situations, ambient light can also be considered as stray light. Stray light is any light that is not intended to be

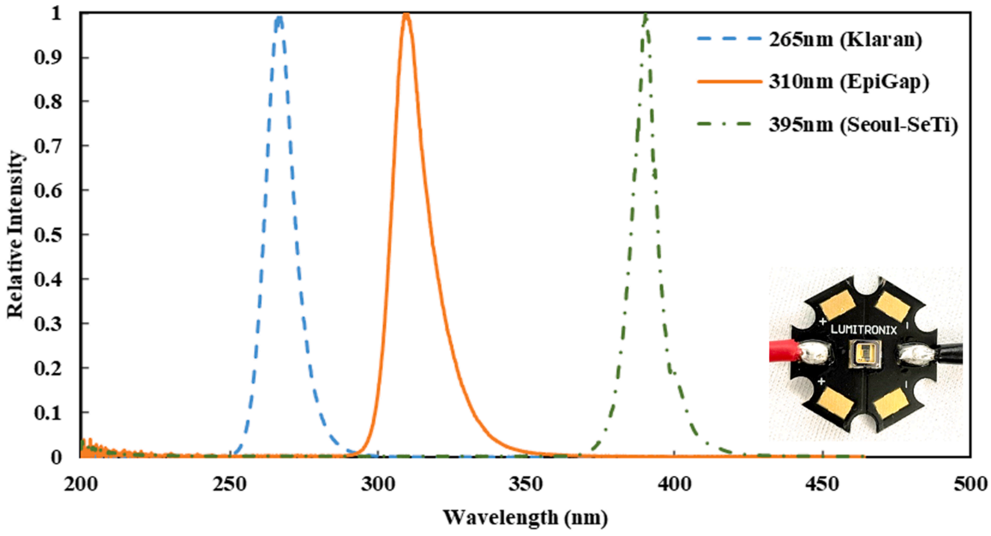


Fig. 3. Relative spectral intensity of each light source.

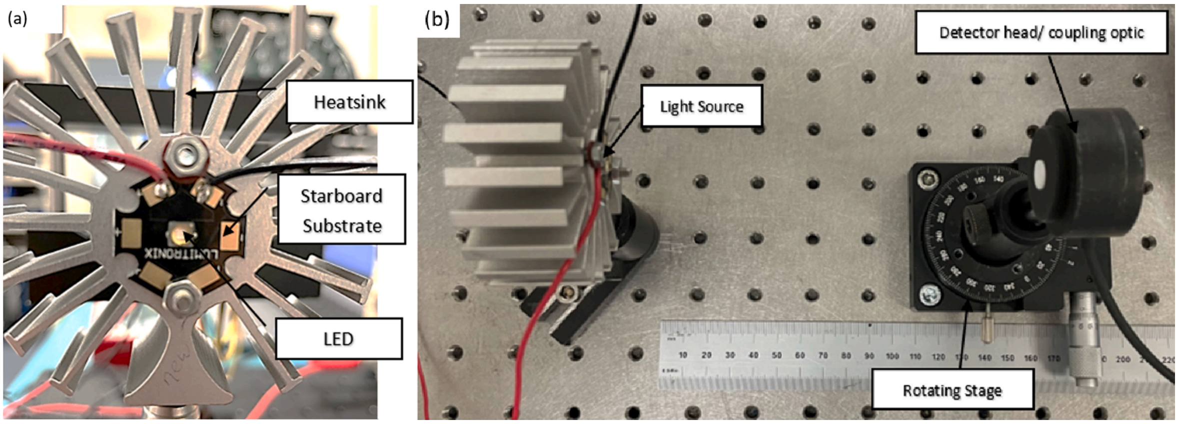


Fig. 4. (a) Light source mounted on the heatsink, (b) Angle of acceptance test set-up using the Ophir detector.

in the system during measurement or operation. It can be light from reflections or scattering from structures and surfaces that cannot be controlled during experiments [14]. This can be controlled by conducting the experiment in a dark room or “zeroing” out the ambient light at the position of measurement, before starting actual measurements. The room in which this experiment was conducted was a well-lit room with ceiling lights and no other light sources in the room. To provide an understanding of how much ambient light exists in a lab environment, each detector was laid flat onto the workbench, and a reading was taken to provide a guide figure on ambient light present in a lab environment.

2.3.3. *Integration time*

Integration time is the period of time over which the detector or coupling optic collects photons of light at every measurement point. This time can range from a few microseconds to seconds. Most power meters and spectroradiometers use auto-integration time settings depending on the amount of light it detects [14]. The manufacturer programmed console within the ThorLabs sensors (PM100D) auto adjusts the range depending on the light input at the aperture so as to return a valid reading for the signal received. On the other hand, the ILT sensor has an option for manual input and the ability to choose an auto setting of integration time to capture data. The integration time settings can be managed via the software interface provided by the manufacturer. Integration time settings can have a significant impact on the data obtained. The same experimental set-up for intensity measurements was used to investigate this effect. These experiments were conducted only for ILT manufactured RAA4 coupling optic as the remaining manufacturers either adjust their range based on the signal or use auto integration time setting.

2.3.4. *Sensor temperature*

The effect of the change in temperature of the sensor on readings was evaluated. For these experiments, a panel resister (10 Ω ± 1% 12.5 W) was mounted onto the back of the ThorLabs S120VC detector head to initiate the required temperature rise. Figure S7 shows a schematic representation of the set-up. The light output was initially allowed to stabilize for 30 min after which the detector head was then heated to 40 °C and readings were taken for each degree celsius drop of the detector head.

2.3.5. *Intensity measured*

Another essential difference between sensors is their ability to return accurate intensity measurements. Different sensors operating in the same wavelength range will return different measured values, and it is critical to know if the intensity displayed is valid within the calibration of the meter. For this purpose, differences in the intensity measurements recorded with the different sensors have been evaluated. For these experiments, the light source was mounted at a 100 mm working distance from the detector, and the intensity was measured (results in Figure S6 of the additional data).

3. Results and discussions

Before any experiments are conducted, it is important to understand non-measurement set-up parameters that can affect the final results. Firstly, the meter chosen must have a traceable and lasting calibration that can be depended upon. Quality of calibration ensures that the conversion of voltage to corresponding light level reading is accurate. Most devices have NIST or ISO17025 traceable calibration [2]. Second, lenses and optics are sometimes used to increase the signal for measurements. Some lenses absorb ultraviolet light, so caution must be taken while using any optics to measure ultraviolet light. As in the case of this study, the lens could only be used to increase the measured intensity from the 395 nm light source and did not increase the measured intensity of light when used with the 265 nm or 310 nm light source. Third, LEDs are known for their ability to turn on and off with less time for stabilization [6]. It is important that readings be recorded after the source has stabilized. It is essential that while designing an experiment, the thermal resistance, specific heat capacity and rate of heat dissipation of the light source are considered and accounted for [1]. Also, it is important to have sufficient thermal management as the LEDs tend to fade off or fluctuate until an equilibrium is reached. An unstable light source can result in inaccurate and non-reproducible measurements. Most sensors are designed to fit a specific application field. The selected sensor must be compatible and fit for the measurement system designed.

3.1. *Angle of acceptance*

In an experiment involving the characterization of an extended light source, the source is normally fixed onto a mounting stand which can then be translated or rotated about an axis. To measure light output and intensity delivered to a point of interest, a suitable detector is placed for measurements. To deduce the angle of acceptance of the detectors/coupling optics used in this study, the light source was fixed while the detector was rotated about an axis. This experiment highlights the importance of accurate positioning of the light source and measuring device for accuracy of measurements obtained. Data were measured for every 10-degree tilt of the detector acceptance plane with respect to the light source. The measured data were then interpolated linearly to steps of 0.1° to calculate the angle of acceptance of the detector/coupling optic. The angle of acceptance has been calculated using the concept of full width half maximum (FWHM) with respect to the light source emission. Fig. 5 shows the angle of acceptance of the detectors discussed earlier.

To understand the results obtained, the designs of these detectors/coupling optics have been taken into consideration (Fig. 5(f)). In the

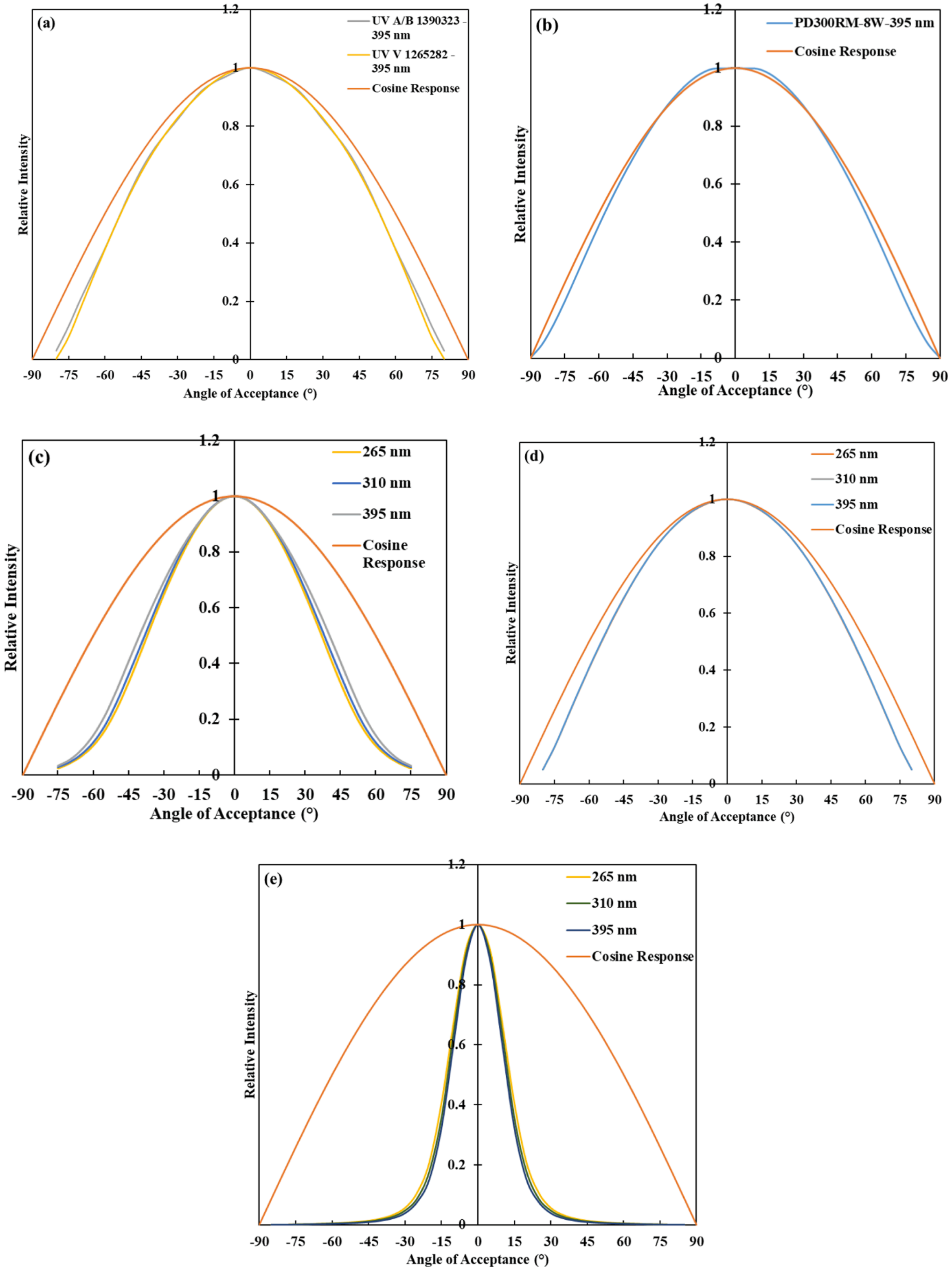


Fig. 5. Angle of Acceptance of sensors– (a) Loctite – UV A/B 1390323, UV V 1265282, (b) Ophir PD300RM-8 W, (c) ThorLabs S120VC, (d) International Light Technologies - RAA4, (e) International Light Technologies - W Optic, (f) Schematic representation of the cross-sectional views of the detectors (not to scale) [18–23].

case of sensors from Thorlabs, Ophir and Loctite, the detectors have an aperture and a detector, while the ILT manufactured coupling optics have a fiber optic which transmits the light incident on the aperture to the detector house inside a box via the phenomenon of total internal reflection. The distance between the detector and aperture and the size of the aperture provides inputs about any light lost within the detector head. Large distances mean that some of the light incident on the aperture will be lost. The measurements have also been compared with

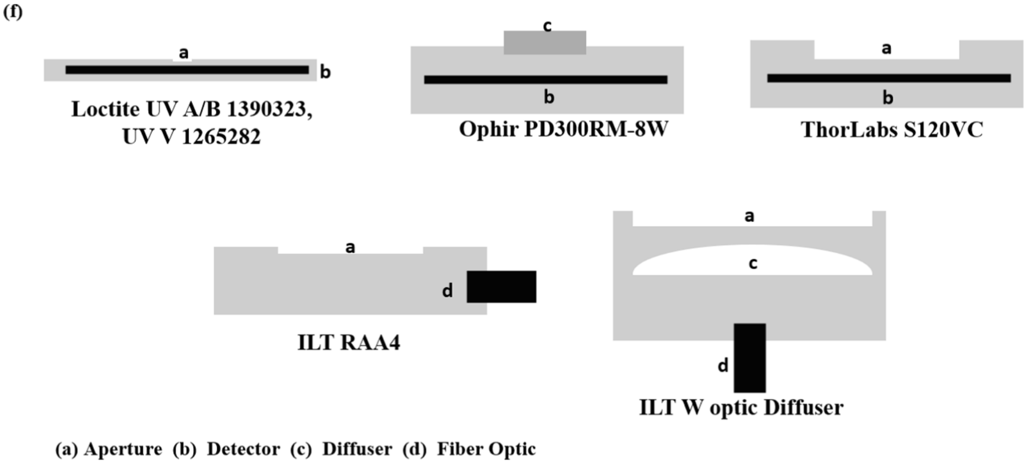


Fig. 5. (*continued*).

an ideal cosine response to understand the behavior of each of the detectors used in the study. Table 2 summarizes the results of the angle of acceptance of detectors in this study.

The Loctite detectors (UV A/B 1390323 and UV V 1265282) have a narrow range of wavelength calibration and have a small aperture diameter. There is very little space between the detector and aperture. This means that most light entering the aperture will reach the detector, thus very little light is lost. It is evident in comparison with the ideal cosine response that it is close to the ideal response (Fig. 5(a)).

In the case of PD300RM-8 W (Fig. 5(b)), the detector is nearly cosine. The angle of acceptance of the detector is 114.5 ± 0.5°, possibly due to a portion of the detector head protruding from the main housing (Fig. 5 (f)). With the diffuser protruding outside of the head, it can accept low angles of light incident onto the diffuser. Low or high angle reflections of light will reach the detector entrance, where it will be scattered onto the detector inside. This makes it ideal to obtain a cosine response i.e., most light reaching its surface will be measured by the detector.

With the ILT RAA4 and ThorLabs S120VC detectors (Fig. 5(f)), the aperture sits a few millimeters inside the front plane of the detector head, which decreases the ability of the sensor to accept low angle light including low angle reflections. For the ThorLabs S120VC detector, the aperture is located lower than that of the RAA4 coupling optic with respect to the detector head which explains the difference in angle of acceptance between the two (Fig. 5(c)). Due to its decreased ability to accept low angle reflections, the ILT RAA4 coupling optic, does not have a near ideal cosine response (109.0 ± 0.5° at 265 nm) as that of the Ophir PD300RM-8 W meaning that this loss needs to be factored in while using the coupling optic in measurements (Fig. 5 (d)). The ILT W optic diffuser has a low angle of acceptance compared to the others in this study (26.5 ± 0.3° at 265 nm (Fig. 5(e))), this can be attributed to the dome-shaped diffuser design of the optic by the manufacturer. It is evident that the distance between the detector and aperture is longer compared to the others, which implies that there is light being lost during transmission. Refer to additional data for analysis points plotted in Fig. 5 (Table S1 – S5).

Table 2
Summary of angular response of detectors.

	Width (°)		
Sensor \ Wavelength	265 nm	310 nm	395 nm
Loctite - UV A/B 1390323, UV V 1265282	N/A	N/A	107.0 ± 0.5
Ophir PD300RM-8 W	N/A	N/A	114.5 ± 0.5
ThorLabs S120VC	74.5 ± 0.5	76.7 ± 0.2	80.7 ± 0.5
ILT RAA4	109.0 ± 0.5	109.0 ± 0.5	109.0 ± 0.1
ILT W Optic	26.5 ± 0.3	24.9 ± 0.2	23.7 ± 0.5

During the experiments, it was observed that two of the detectors (W Optic and S120VC) showed a wavelength dependent angular response (Table 2). The ILT W Optic diffuser had a larger angle of acceptance towards shorter wavelengths, while the ThorLabs S120VC showed a larger angle of acceptance towards the longer wavelength light (Fig. 6 (a)).

In the case of the ThorLabs S120VC detector, the decrease in angle of acceptance with the decrease in wavelength can be associated with the absorption and scattering element within the detector. It is possible that the material of the detector does not scatter the lower wavelengths enough, and the interactions between light and detector inside are

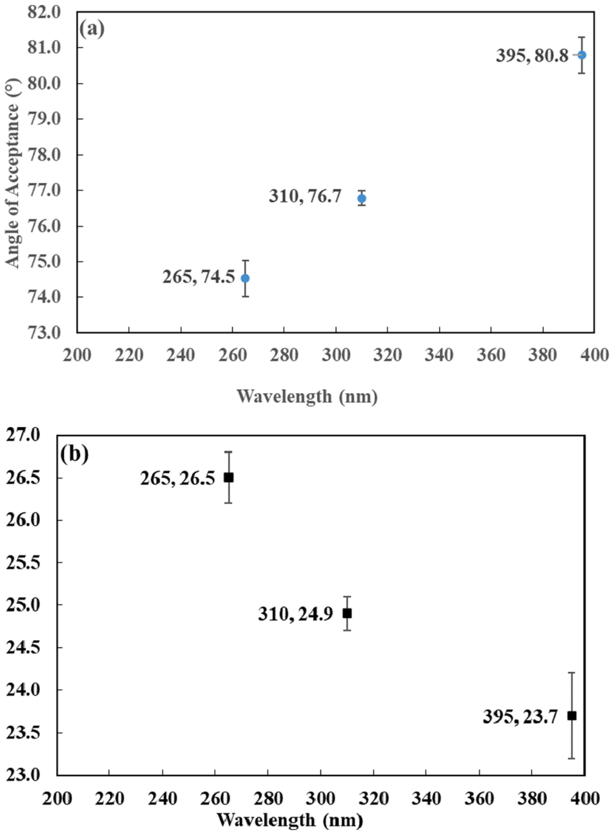


Fig. 6. Change of acceptance angle of detectors with wavelength. (a) ThorLabs S120VC, (b)ILT W Optic Diffuser.

causing this decrease of angular response combined with predominant optical loss due to Rayleigh scattering [24,25]. As discussed earlier, the ILT manufactured optics employ an optical fiber to transmit light received to the detector housing. While no change in angle of acceptance with wavelength was observed with the RAA4 optic, the W optic diffuser measurements recorded a decrease with the increase in wavelength (Fig. 6(b)). This could be due to the phenomenon of Brillouin shift within the optical fiber that needs to be investigated separately [26]. These are just possible reasons for the changes observed and the effect on the actual values measured corresponding to each wavelength needs to be investigated separately, as it is outside the scope of this paper.

As discussed in this section, it can be seen that it is essential to ensure that that the detector is flat and the back plane is parallel to the source and perpendicular to the optical axis. This ensures the credibility and accuracy of measurements. A small degree tilt in the detector could cause a significant change in measurements that will affect further calculations or further use of the data, especially in the case of extended sources of light.

3.2. *Effect of ambient light*

Measurements in ambient light can be challenging, as this light can be detected by the measuring device, thus impacting the final measurement result. Even stray light reflecting off surfaces or lab coats can be detected. Reflections from uncoated surfaces (~5%) or coated (~1%) surfaces can affect data measured by the optical sensor. Accounting for changes in ambient light when the source signal is at a comparable level to that of ambient light poses a big challenge to researchers. Ambient light in the room will be an issue if the ambient signal is large, as this will lower the detection range for the detector/sensor. For example, if a detector can only measure up to 20 mW cm^{-2} of intensity and the ambient light measured is about 15 mW cm^{-2}, it leaves the detector with only 5 mW cm^{-2} for the signal of interest.

Some meters or dosimeters are calibrated for a specific wavelength range (ex. Loctite UV A/B 1390323) while others are calibrated for a broad wavelength range (ex. ILT 950 UV, ThorLabs S120VC). This means that the meter reads any ambient light in the calibrated wavelength range (i.e., for ILT and ThorLabs 200 nm to 1100 nm). It is known that there is negligible UV-C light in solar but due to the range of calibration of the meters, most of the surrounding light can be read by the detectors/sensors. For low efficiency UV-C LEDs, the signal is very low in comparison to other wavelength ranges. Therefore, it is important to account for the surrounding light to ensure the measured data is accurate. This measurement was carried out to demonstrate how large an ambient light signal can be in a lab environment. (For data on these measurements, refer to Table S6 in additional data). While the Thorlabs, Ophir and ILT sensors detected ambient light and data could be drawn, the Loctite detectors (UV A/B 1390323, UV V 1265282) detected no ambient light due to two reasons. One, Loctite detectors are calibrated for narrow band wavelength range with possible inbuilt filters that filter-out of band wavelengths and second, detection range (5 mW cm^{-2} to 20 W cm^{-2}) which makes the detectors less susceptible to low ambient signals.

In the experiments conducted, it has been observed that typical ambient levels were approximately ~ 0.23 mW cm^{-2}. There can be a significant difference in readings, specifically for deep UV source measurements, if ambient light is not taken away from the measurements. For example, for the 310 nm LED used in this study, at a working distance of 100 mm, the recorded intensity was 0.13 mW cm^{-2}. If ambient light is not accounted for, the recorded intensity would have been 0.36 mW cm^{-2}. The increase in measured reading is approximately 180% more than the actual amount of source light received by the detector. This measurement is simply a guide figure to emphasize the importance of accounting for ambient light in any data being captured.

Most detectors (ex. ThorLabs sensor) have a function to “zero” before conducting any measurements. This option helps detect ambient light and subtract the small fraction out during actual measurements. Some detectors (ex. ILT sensors) in the market employ a preliminary dark scan measurement before the measurement scan. A dark scan is any signal present in the room in the absence of light. These scans are subtracted from the measured scan to provide data on source light observed by the detector. The ILT detectors use a USB interfaced device with a custom controlled computer software tool – SpectrILite III, that assists in measurement using the detectors. The software shows the ambient light (positive peaks) and dark signal (subzero peaks) detected by the detector. There are 2 peaks, at 405 nm and 435 nm, in the frame. The intensity measured in the figure has been contributed by reflections from ceiling lights, stray light and mercury lines from the fluorescent tubes (Refer to Figure S9, additional data).

Sometimes, in the case of open ceilings, the weather outside the building could affect the ambient light in the room. A rainy day could mean very little ambient light, which needs to be considered while taking measurements. It is possible to disregard ambient light conditions while taking measurements if there is a sufficient signal, but precautions must be taken to keep the surrounding light as consistent as possible. All experiments for the other parameters discussed in the paper took place in a dark room and any ambient light was “zeroed or subtracted” using the respective power meter.

3.3. *Effect of integration time on readings*

Among all the sensors used in this study, only the coupling optics from ILT required the manual input of integration time for measurements. Control of integration time helps to maximize the signal-to-noise ratio and avoid sensor saturation. Signal-to-noise ratio (SNR) is a quantity that compares the level of the light signal received by the detector to the level of background noise. A higher SNR means that there is more signal than noise and vice versa [17]. Saturation occurs when the signal exceeds the measurement capacity of the sensor.

Fig. 7 shows the difference between a saturated and an unsaturated sensor. When the intensity exceeds the upper limit of the detection system, saturation occurs which is recognizable by a flat line (see dotted curve in Fig. 7). The data in Fig. 7 is from the RAA4 coupling optic measuring a 395 nm light source. At 250 ms integration time, the detector measured data for longer than its measuring capacity, causing it to saturate, whereas at 10 ms integration time, the detector measured data within its capacity. To understand the difference in measured intensity for a saturated and unsaturated sensor, a single scan was taken. Intensity scans with a saturated sensor resulted in a reading that was 43% less than that of the unsaturated sensor. The difference in measured intensity demonstrated the need to determine an ideal integration time before collecting data. In certain cases, depending on the measurement set-up, saturation can also be rectified by reducing the intensity of the source or increasing the distance between the source and detector.

It is also important to have the right integration time during measurements. Integration times depend on, but are not limited to, the current supplied to the LEDs, the optical output from the source and the efficiency of the optical system. Lower integration times result in a lower signal-to-noise ratio, while higher integration times risk saturation of the sensor. The experiment was conducted to understand the effect of integration time on the measurements using the ILT RAA4 coupling optic for 2 wavelengths, 265 nm and 395 nm. Fig. 8 shows the plots of the relative intensity measured against increasing integration time tested using the optic. All data presented in Fig. 8(a) are relative to the intensity measured at an integration time of 1 ms. All data presented in Fig. 8(b) are relative to the intensity measured at an integration time of 10 ms (raw data in additional data Table S7 and S8). The data in Fig. 8 was measured on three separate days and has been extracted from the ILT SpectrILite software. Measured data were seen to be consistent up to 3 significant digits after the decimal point.

For the 395 nm LED source, the integration time was varied between 0.03 ms and 20 ms. An integration time higher than 20 ms resulted in a

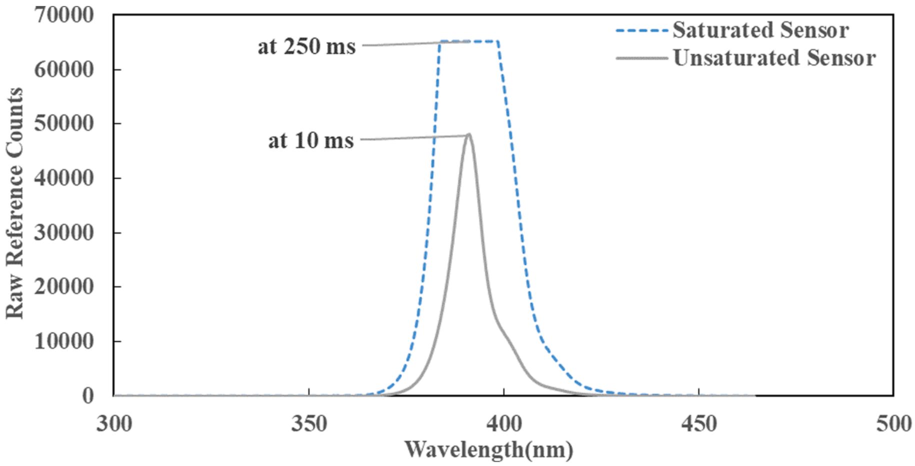
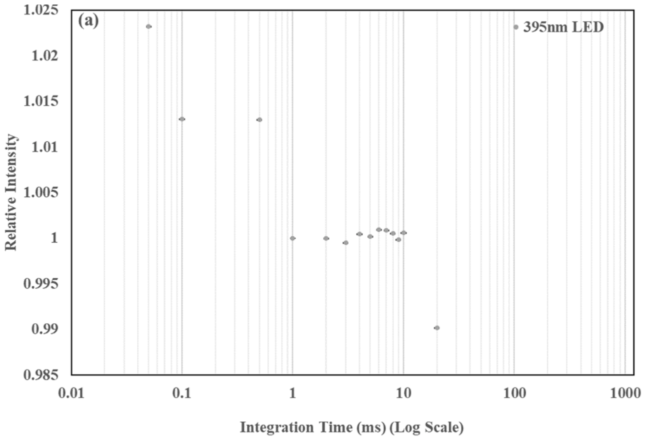


Fig. 7. Raw reference counts as measured by a saturated and unsaturated sensor.



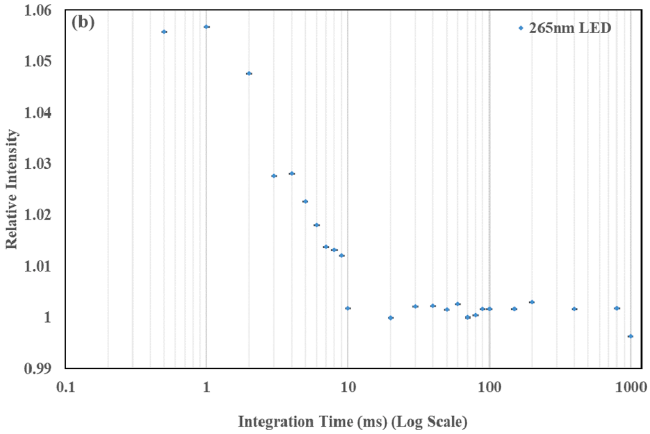


Fig. 8. Change in measured intensity with integration time (a) 395 nm and (b) 265 nm.

saturated sensor as 395 nm LED is efficient and emitted a high signal compared to the 265 nm and 310 nm LEDs. It was observed that at an integration time lower than 10 ms, the intensity measured was nearly constant. At an integration time of less than 1 ms, the signal-to-noise ratio was very low, and hence the intensity measured is not a valid measurement of the source light. In the case of the 265 nm LED source, the integration time was varied between 0.03 ms and 1500 ms. Due to the low light output of the source, higher integration times were used to understand the impact. It was observed that at an integration time lower than 40 ms, the intensity measured was nearly constant. Similar to the 395 nm LED, at integration times less than 10 ms, it was observed that the measurement recorded too much noise. It is important to note that these integration times are ideal at a working distance of 100 mm only and will vary with any change in working distance between the source and measuring sensor.

3.4. *Effect of temperature of the sensor on data*

Detector heads can slowly heat up with time when exposed to light. Temperature changes can significantly affect the readings displayed by the power meter. Sensors and meters used for measuring light are commonly made of semiconductor materials that are prone to deterioration upon heating or significant temperature rise of the body of the sensor. Prolonged exposure to light can lead to deterioration of the respective filter or aperture within the sensor. This deterioration can lead to permanent damage to the sensors and hence needs to be monitored carefully during measurements. Most meters do not display the temperature of the detectors. Amongst the sensors used in this study, ThorLabs PM100D power meter could display temperatures. To understand the effect of temperature on the sensor, the ThorLabs S120VC detector was heated to 40 °C using a panel resister, and the signal from the 395 nm LED source was monitored while the detector started to cool. The room temperature during this experiment was fixed at 20 °C.

Data from the experiment can be seen in Fig. 9. All data measured have been normalized to the room temperature reading. The results from the experiment showed that there is an average of 0.2% change of measured intensity when the temperature rises. The change is low compared to change seen in integration time experiments, but this provides a valuable understanding of how temperature impacts data

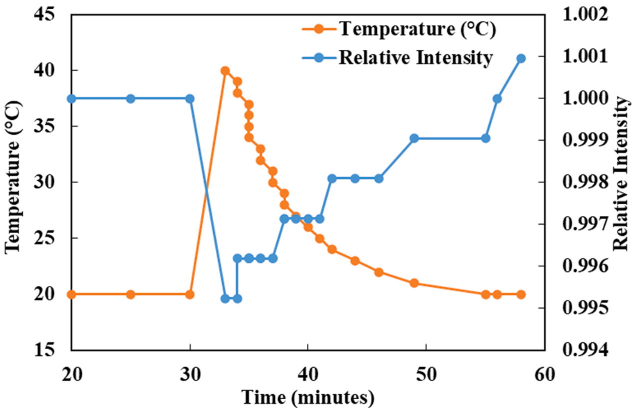


Fig. 9. Effect of temperature on intensity measured by the sensor.

measured by the detector. It is also possible that there is a temperature compensator designed into the detector head. Since, the experiment employed artificial heating on the back of the detector, so as to not harm the detector permanently, it is possible that the change in measured data is a lot higher when the detector is heated over a prolonged time (refer Table S9 in additional data for experimental values).

Another reason for the low change in intensity reading could be due to the mechanical design of the detector. While the display temperature does rise due to the heat applied, the light entering part of the detector could be at a much lower temperature. Furthermore, the light source needs a certain amount of time to stabilize. It is important to note that no significant error was observed in the data measured between experiments, possibly due to artificial heating and a reading of only 3 significant digits after the decimal point. Although this may change when the sensor temperature rises due to the light source. To avoid inaccurate readings, it is recommended to shield the detector from light until the source stabilizes.

3.5. Differences in intensity measurements between sensors

Table 1 lists the intensity ranges of each sensor studied in this paper. This experiment was conducted to show the difference in values returned by each sensor. Thorlabs and ILT manufactured sensors captured all the wavelengths used in this study, whereas the others could only detect the 395 nm LED light source. All measurements were taken on three separate days to evaluate repeatability and accuracy, and averaged before plotting them in Fig. 10. For comparable data between detectors in this study, a separate experiment was conducted using a magnified signal for Thorlabs and Loctite Detectors.

To ensure reproducibility of data, calculated error between measurements and between consecutive days of measurement was observed to be 1% between the measurements. Data measured by ThorLabs Sensor (S120VC) has been used as a normalization point for the graph plotted in Fig. 10 as the average radiometric accuracy of the detector is approximately 5% across the entire range of wavelengths in this study. For the 395 nm LED source, the Ophir and Thorlabs sensors are in good agreement of ± 6% with each other. Even though all the sensors used have the ability to detect intensities in the range of the 395 nm LED source, all of them return different values. For Loctite detectors, given their higher angle of acceptances, it can be seen that they measure higher intensities relative to the ThorLabs sensor measurements. The Loctite detector UV A/B 1390323 measured approximately 17% higher intensity while the UV V 1265282 measured 70% higher intensity compared to the Thorlabs S120VC sensor.

It is evident from Fig. 10 that the RAA4, which is a right-angle cosine receptor, captures data very close to that of the ThorLabs sensor (a difference of ± 5%) while the W optic diffuser returns data approximately 20% lower than the ThorLabs sensor. Due to the lower angle of acceptance of the W optic, it is evident that less light is detected by the head and thus it is important to understand its compatibility and calibration before use in an application. For the 265 nm and 310 nm LED sources, only the RAA4, W optic and S120VC detector heads could be used. It was also observed that even though the RAA4 has a higher angle of acceptance than the S120VC, for the 310 nm source, the data measured was lower. This could be due to the radiometric accuracy of the two devices specified by the manufacturers, ±20% and ± 5%, respectively.

3.6. Recommendations

The light industry is moving towards a common standard for light measurements in the form of LM-92, which is a new lighting measurement standard developed by Illuminating Engineering Society (IES) and International Ultraviolet Association (IUVA) [27]. It is important to understand the differences between different sensors when comparing results between studies or evaluating UV-LED based systems for purchase where manufacturers state the system irradiance and energy density. While there are multiple options available for both the kind of meter and sensor measuring the light source, key importance must be given to the kind of application and set-up available to the user. The concept of extended light source needs to be applied while measuring large sources of light to ensure most light irradiated is captured by the detector. The kind and material of the detector must be looked into while choosing the measuring system. A close to cosine receptor is highly recommended as this means most light emitted by the source will be captured by the detector, if not, other errors are in the system and need to be factored in calculations. The concept of ambient light must be considered while measuring low light signal sources as this can significantly change the measurement obtained. Although LEDs are known to have instant ON/OFF capability, it is recommended to shield the light sensor from the source while it stabilizes before measurements so as to not damage the sensor during measurements. Not all sensors/coupling optics behave the same between different manufacturers and care must be taken while comparing measurements at all times.

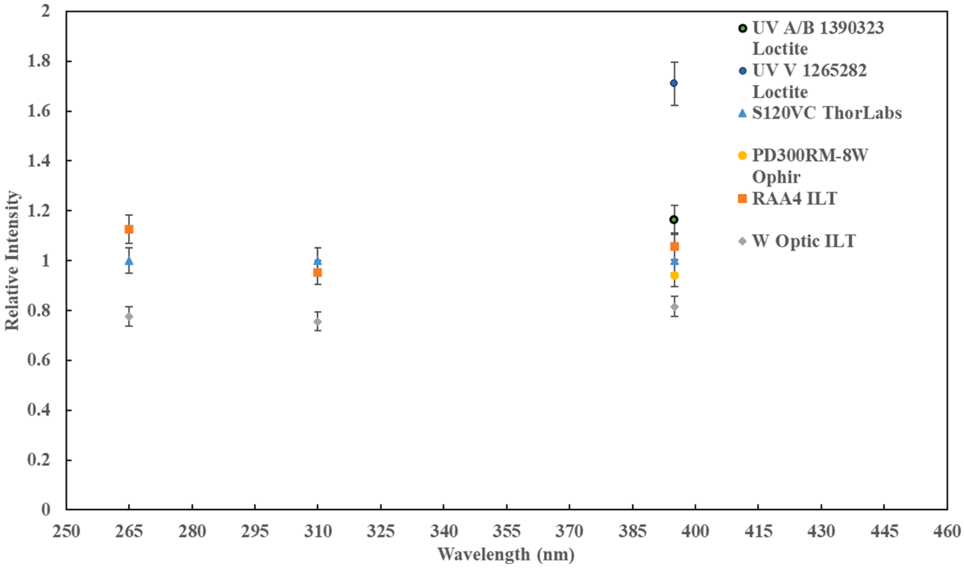


Fig. 10. Comparison between sensor measurements.

4. Conclusion

This study shows that there are significant differences between sensors from different manufacturers used in the measurement of ultraviolet light systems. The paper evaluated the different angular responses of the sensors and related them to their mechanical designs to understand the reason behind the response. The study shows that some sensors can have different angular responses to different wavelengths and highlights the effect of ambient light on readings. The study observed that, for the ThorLabs sensor, there is a difference of 0.2% in the readings for a temperature rise of 20 °C. This study also observed that even though two sensors can have the same wavelength ranges, it is not necessarily true that the readings will be the same. As seen for the 265 nm LED, an average difference of 17% between measured data from different sensors operating in the same wavelength range. We concluded that measurement results are application specific and need to be evaluated first before proceeding towards characterizing the light source. For extended light sources, it is important to consider the angle of acceptance of the detectors and the working distance to ensure data is captured accurately. Change in angle of acceptance with wavelength was seen for the ThorLabs S120VC and ILT W Optic diffuser. The reason behind this change needs to be investigated further.

LED output can change with time, and the ability to measure a wide range of light signals is important to keep in mind while selecting a power meter. Measurements taken and data recorded need to be used and interpreted correctly before further use. Ensuring that the sensor is positioned precisely with respect to the source provides some assurance that the data received is accurate. Interpretation of the data recorded plays a key role in further use of the measurements. The study also highlighted the importance of ensuring the compatibility of the sensor with the specific application.

CRediT authorship contribution statement

Adithya Pai Uppinakudru: Investigation, Methodology, Data curation, Writing – original draft. **Ken Reynolds:** Conceptualization, Supervision, Resources, Writing – review & editing. **Simon Stanley:** Supervision, Validation, Resources, Writing – review & editing. **Cristina Pablos:** Validation, Supervision, Writing – review & editing. **Javier Marugán:** Validation, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.measurement.2022.111278.

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