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Measuring Low-Order Photometric Parameters of Light Fields: Methods Exploration and Simulations

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ABSTRACT Low-order photometric parameters of light fields are important aspects determining lighting qualities but difficult to be measured. In this article, we did a systematical investigation into the performance of a cubic meter and a tetrahedron meter as well as an HDR panoramic map-based method in simultaneously recovering light density, direction, and diffuseness. Five metrics were introduced with two based on the measurement using a cubic illumination meter, two based on a tetrahedron shaped illumination meter and one based on SH decomposition of HDR panoramic maps. Furthermore, the measurement of five metrics was simulated under six HDR Panoramic maps of natural scenes in various postures which mimic the complexity of real environments. The results indicate that the measurement of low-order photometric parameters of light fields using Spherical Harmonics (i.e. latter referred to as SH) decomposition of HDR panoramic map gave the most reliable results. The tetrahedron meter based metrics gave more robust results in the measurement of light density while the cubic meter based metrics performed better when measuring light direction. This study also provides a solution for a more robust measurement of light diffuseness based on the ratio between the vector strength measured with a cubic meter and light density measured with a tetrahedron meter. With the quick development of high-speed built-in camera and mobile computing techniques, this research provides confidence in developing applications in mobile phone by capturing HDR panoramic maps or built in light meters to measure the low-order photometric parameters of light fields in 3D spaces.

INDEX TERMS Lighting, light density, light direction, light diffuseness, HDR panoramic map, spherical harmonics, mobile application, cubic meter, tetrahedron meter, 360-degree picture.

I. INTRODUCTION

What determines lighting effects? Once the light is emitted from its source, it starts a journey, interacting with its surroundings. The interactions between light and scenes result in so-called light fields. This physical concept was first introduced by Gershun in 1936 in a Russian article then published in an English translation three years later [12]. According to Gershun's concept, the light field is essentially a 5-dimensional function that describes the light traveling in every direction through any point in space if color and temporal variations are neglected.

In the traditional lighting engineering, the illuminance incident on a surface is the most widely used electric lighting design criterion. Particularly, the horizontal illuminance has drawn the most attention. However, as the lighting profession stepped into the third stage, instead of taking light simply as a provision for visibility, people expect light to serve as a medium that conveys content, both informative and emotional [3], [7], [8]. Since the light field shapes the visual appearance

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of the scenes and the objects inside the scenes, lighting professionals should pay more attention to the light distribution around the lit object instead of just caring about illuminance on a specific plane.

The light field (essentially the light distribution) in natural scenes is highly complicated due to the interplay between lighting, geometry and materials, which strongly influence the appearance of a scene and the visual experiences inside this scene. Nonetheless, research also shows that the human observers is able to distinguish the intensity, the primary illumination direction, and the diffuseness, which are three basic properties of light [15], [20], [26], [27]. These three properties were found to be determined by the low-order frequencies of the light distribution and also be called low-order photometric parameters of light field. In this article, we introduced the measurements of these three basic light properties using different methods and equipment.

The ''intensity'' is described as ''radiant flux density'' according to Gershun's theory and also called as light density. It describes a constant illumination from all directions. The ''light vector'' describes the average illumination direction and strength. ''Diffuseness'' of light was not mathematically described by Gershun or Mury but by Xia et al using spherical harmonics decomposition [24], [25]. The light diffuseness can range from fully collimated via hemispherical diffuse to completely diffuse light. Direct sunlight generates collimated light, while an overcast sky is a typical example of hemispherical diffuse light and a polar whiteout of completely diffuse light.

Then, this raises the question in what convenient way the physical light distribution can be measured properly. One of the most widely accepted method was proposed by Cuttle [6], [9], which enables exact measurement of the illuminance vector direction and magnitude by a fixed device named cubic meter, as well as providing a useful basis for calculating the illuminance density and diffuseness. However, tests using point light sources show Cuttle's method yielding an inexact estimate of the illuminance density [18] which might also lead errors to the estimate of light diffuseness. In our previous research [25], a domed-shaped light source was simulated to test the performance of Cuttle's method in measuring the light diffuseness. The result also showed errors especially when measuring relative direct light (i.e. when the area of the dome light is small). Furthermore, it was found that, still using cubic meter's measurement, an approach fitting the first two orders of Spherical Harmonics (SH) representation of the light fields has reduced the errors. Thus, how the SH based method would perform on measuring other low-order photometric parameters would be interesting to investigate. William Thomas Singleton in his book ''The body at work: Biological ergonomics'' written in 1982 has mentioned that the average of the illuminance on the four sides of a regular tetrahedron can approximate the ''scalar illuminance'' [22]. But since then, no further work about the use of a regular tetrahedron to measure light density was conducted. In this research, we explored practical methods to simultaneously measure the low-order photometric parameters of light field (i.e. light density, direction and diffuseness). Within which, two of the methods were based on the use of a cubic illuminance meter, two of them were based on the use of a tetrahedron shaped meter and one based on spherical harmonics decomposition of HDR (High Dynamic Range) panoramic maps. Real lighting environments are far more complicated than the simulated simple ones. Thus, all of the methods mentioned above will be simulated under HDR panoramic maps mimicking the complexity of real lighting environment.

With the quick development of digital photography, computer graphics and mobile computing techniques [16], [17], the development of mobile multimedia systems and applications could potentially affect many domains [29]. For example, in lighting industry, the shooting of HDR panoramic images becomes more and more easily using a mobile phone. It also becomes possible using plug-in devices and sensors inside phone to simulate the function of a cubic meter or a tetrahedron meter [21]. Thus, the measurement of low-order photometry using panoramic HDR maps, cubic meter or tetrahedron meter expected to have a wide application prospect in the near future.

II. THEORY

A. HDR PANORAMIC MAP-BASED METHOD

High dynamic range image (i.e. HDRI) can represent similar range of luminance to that experienced through human visual system. The HDR panoramic map can be seen as a measure of luminance as a function of directions in the 3D space. They can be used as image-based lightings and are important for realistic renderings [4], [11]. Moreover, HDR panoramic maps can be reconstructed by the sum of their spherical harmonics (SH) components. Meanwhile, how the low-order photometric parameters are related in the resulting SH decomposed light field was found.

The zeroth order component of the SH decomposition of light fields represents the flux density arriving at the measured point. Cuttle used ''illumination scalar'' (i.e. E_{scalar}) to describe the flux density arriving at this point [6], [9]. According to the previous research [24], the relationship follows:

$$E_{scalar} = \frac{\sqrt{\pi}}{2} d(L_0) \tag{1}$$

where $d(L_0)$ is the strength of the zeroth order component of the SH decomposition of incident light distribution.

The first-order component of the SH approximation of the light field can be transformed into linear functions of the Cartesian coordinates (x, y, z) as follows:

$$\begin{cases} SH_1^{-1}(\vartheta, \varphi) = -\sqrt{\dfrac{3}{4\pi}} sin\vartheta\, sin\varphi = -\sqrt{\dfrac{3}{4\pi}} y \\ SH_1^{0}(\vartheta, \varphi) = \sqrt{\dfrac{3}{4\pi}} cos\vartheta = \sqrt{\dfrac{3}{4\pi}} z \\ SH_1^{1}(\vartheta, \varphi) = -\sqrt{\dfrac{3}{4\pi}} sin\vartheta\, cos\varphi = -\sqrt{\dfrac{3}{4\pi}} x \end{cases} \tag{2}$$

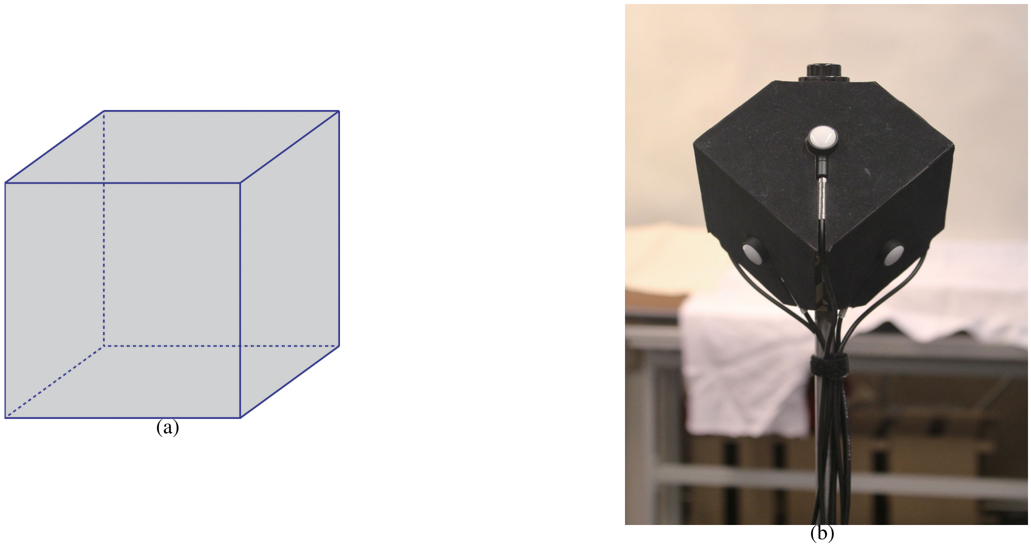

FIGURE 1. (a) The base of a cubic meter (b) the actual cubic meter in the lab built by attaching an illuminance meter on each of the six faces of a cube.

Thus, the average direction of the incident light around the measured point can be extracted through the first-order component and the illumination projected on this point shares the same average direction (i.e. light vector). Meanwhile, the relationship between the strength of the first-order components and the magnitude of the light vector is:

$$E_{vector} = 2\sqrt{\frac{\pi}{3}}d(L_1) \tag{3}$$

where $d(L_1)$ is the strength of the first-order components of the SH decomposition of luminance distribution and can be calculated using:

$$d\left(L_1\right) = \sqrt{\sum_{m=-1}^{1}(L_1^m)^2} \tag{4}$$

In our previous research [24], [25], it was proved that the ratio between the strength of the first-order and zeroth-order components of the SH representation (D_{Xia}) gives the diffuseness. It can be measured according to D_{Xia}, which is derived from the luminance distribution of the light field. The final normalized form of D_{Xia} to range "0" to "1" is:

$$(D_{Xia})_{Normalized} = 1 - d(L_1)/d(L_0)/\sqrt{3} \tag{5}$$

with "0" indicating fully collimated light and "1" indicating the fully diffuse.

B. CUBIC ILLUMINATION METER-BASED METHOD

The base of a cubic illuminance meter is shown in Figure 1 (a) and the actually built cubic meter in the lab with Konica-Minolta T-10MA illuminance meters is shown in Figure 1 (b).

1) CUTTLE'S METHOD

The spatial illuminance distribution about a point can be described using illuminance solid and it depicts how the illuminance at a point varies according to the direction of the measuring surface. Furthermore, "illumination scalar" (i.e. E_{scalar}) was used by Cuttle to describe the flux density arriving at this point [6]. The illumination solid at any illuminated point in a space can be separated into two components: the vector component (i.e. $\mathbf{E_{vector}}$) and symmetric component (i.e. $E_{symmetric}$). Thus, the "illumination scalar" is the contribution of both the vector and the symmetrical components.

One of the methods to measure the illumination vector and scalar, as well as the ratio between illumination vector and scalar (i.e., the inverse of the light diffuseness) was proposed by Cuttle [6], [9]. This method requires six illuminance values in three mutually perpendicular directions to be measured, being $E_{(x)}, E_{(-x)}, E_{(y)}, E_{(-y)}, E_{(z)}, E_{(-z)}$. Thus, a cubic illumination meter was used and the illumination vector component can be calculated as:

$$\mathbf{E_{vector}} = (E_{(x)} - E_{(-x)}, E_{(y)} - E_{(-y)}, E_{(z)} - E_{(-z)}) \tag{6}$$

Furthermore, the scalar component as:

$$\begin{aligned} E_{scalar} &= \frac{|\mathbf{E_{vector}}|}{4} + \bar{E}_{symmetric} \\ &= \frac{|\mathbf{E_{vector}}|}{4} + \frac{MinSum}{3} \end{aligned} \tag{7}$$

within which:

$$\begin{aligned} MinSum = min(E_{(x)}, E_{(-x)}) + min(E_{(y)}, E_{(-y)}) \\ + min(E_{(z)}, E_{(-z)}) \end{aligned} \tag{8}$$

where "min" means the minimum. As a consequence, the vector/scalar illumination ratio proposed by Cuttle varies from "4" to "0" and the normalized form of Cuttle's diffuseness metric is:

$$(D_{Cuttle})_{Normalized} = 1 - (|\mathbf{E_{vector}}| / E_{scalar})/4 \quad (9)$$

with "0" corresponding to fully collimated light and "1" corresponding to fully diffuse light.

2) XIA'S METHOD

A similar but differently framed approach was proposed by Xia *et al.* [25], which can simultaneously recover the low-order properties of the light field based on SH representation of the light field.

According to the HDR panoramic map-based method, the first two orders (i.e. the zeroth-order together with the first-order) of the SH representation of the light field are sufficient to recover the light density, direction and diffuseness. The cubic illumination meter yields six illuminance values due to six illuminance meters mounted on its faces (i.e. $E_{(x)}, E_{(-x)}, E_{(y)}, E_{(-y)}, E_{(z)}, E_{(-z)}$). To generate the illuminance values, the illuminance meters have a certain angular sensitivity profile that should be convoluted with the incident light distribution on that illuminance meter. Each illuminance meter's angular sensitivity profile follows the cosine law as a function of the angle between the incident direction of light and the normal to the surface to which the meter is attached. Moreover, the sensitivity profile can also be decomposed into SHs (see the first matrix in equation 10). Because of the orthonormality of the SHs basis function, we finally get a system of six equations with four unknown coefficients (i.e. the coefficients of the zeroth-order SH_0 plus the first-order components SH_1^{-1}, SH_1^0 and SH_1^1, see the second matrix in equation 10)). By using a least square approach, solutions for the overdetermined system can be fitted. Thus, the zeroth-order and first-order modes of the SH representation of the light field can be recovered. It carries the information about the flux density (i.e., the zeroth order), light vector (i.e., the first-order) and the diffuseness.

$$\begin{bmatrix} (S_x)_0 & (S_x)_1^{-1} & (S_x)_1^0 & (S_x)_1^1 \\ (S_{-x})_0 & (S_{-x})_1^{-1} & (S_{-x})_1^0 & (S_{-x})_1^1 \\ (S_y)_0^0 & (S_y)_1^{-1} & (S_y)_1^0 & (S_y)_1^1 \\ (S_{-y})_0 & (S_{-y})_1^{-1} & (S_{-y})_1^0 & (S_{-y})_1^1 \\ (S_z)_0^0 & (S_z)_1^{-1} & (S_z)_1^0 & (S_z)_1^1 \\ (S_{-z})_0 & (S_{-z})_1^{-1} & (S_{-z})_1^0 & (S_{-z})_1^1 \end{bmatrix} \times \begin{bmatrix} L_0 \\ L_1^{-1} \\ L_1^0 \\ L_1^1 \end{bmatrix} = \begin{bmatrix} E_x & E_{-x} & E_y & E_{-y} & E_z & E_{-z} \end{bmatrix}^T \quad (10)$$

As a consequence, the ways to calculate illumination scalar, vector and diffuseness according to equation 1, equation 2, equation 3 and equation 5 can be used.

C. TETRAHEDRON SHAPED METER-BASED METHOD

In the preceding section, both methods can recover the flux density, light vector and diffuseness based on the measurements of a cubic meter. The theory behind Cuttle's method approximately estimates the illumination and the theory behind Xia's method fits the first two orders approximation of the SH representation of the luminance distribution. Besides using the cubic meter, there was researcher finding that the average illuminance on four sides of a regular tetrahedron was quite close to the scalar illuminance [22]. Furthermore, we found that the first four coefficients of the first two order SH representation can be fitted approximately based on the four measurements on a tetrahedron. As a result, we wonder whether a regular tetrahedron shaped illuminance meter covers enough directions to measure the zeroth-order and first-order SH properties of the light field.

The tetrahedron illuminance meter can be built by attaching illuminance meter on each of the four faces of a regular tetrahedron shown in Figure 2.

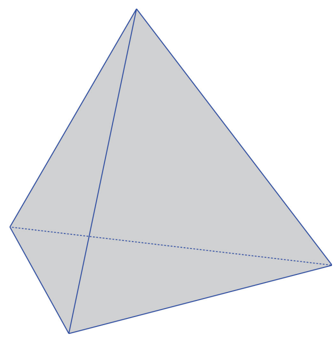

FIGURE 2. The tetrahedron shaped illumination meter can be built by attaching an illuminance meter on each of the four faces of a regular tetrahedron.

1) PHYSICAL APPROXIMATION OF ILLUMINATION METHOD

In one way, we calculated the scalar component by averaging the illuminance of the four faces of the regular tetrahedron. We calculated the vector component by projecting the four measurements in a Cartesian coordinate system. After that, we extracted the direction information out. The diffuseness was related to the ratio between the vector strength and scalar illumination, which can be normalized according to equation 9.

2) FIRST TWO ORDERS APPROXIMATION OF SH-BASED METHOD

In the other way, based on the four measurements on a regular tetrahedron, we get a system of four equations with four unknown coefficients (i.e. the coefficients of the zeroth-order SH_0 plus the first-order components SH_1^{-1}, SH_1^0 and SH_1^1), as shown in equation 11. Then, the first four coefficients of the first order SH representation of the light field can be obtained. In the same way, the illumination scalar, vector and diffuseness can be calculated according to equation 1, equation 2, equation 3 and equation 5.

$$\begin{bmatrix} (S_{T1})_0 & (S_{T1})_1^{-1} & (S_{T1})_1^0 & (S_{T1})_1^1 \\ (S_{T2})_0 & (S_{T2})_1^{-1} & (S_{T2})_1^0 & (S_{T2})_1^1 \\ (S_{T3})_0^0 & (S_{T3})_1^{-1} & (S_{T3})_1^0 & (S_{T3})_1^1 \\ (S_{T4})_0 & (S_{T4})_1^{-1} & (S_{T4})_1^0 & (S_{T4})_1^1 \end{bmatrix} \times \begin{bmatrix} L_0 \\ L_1^{-1} \\ L_1^0 \\ L_1^1 \end{bmatrix} = \begin{bmatrix} E_{T1} & E_{T2} & E_{T3} & E_{T4} \end{bmatrix}^T \quad (11)$$

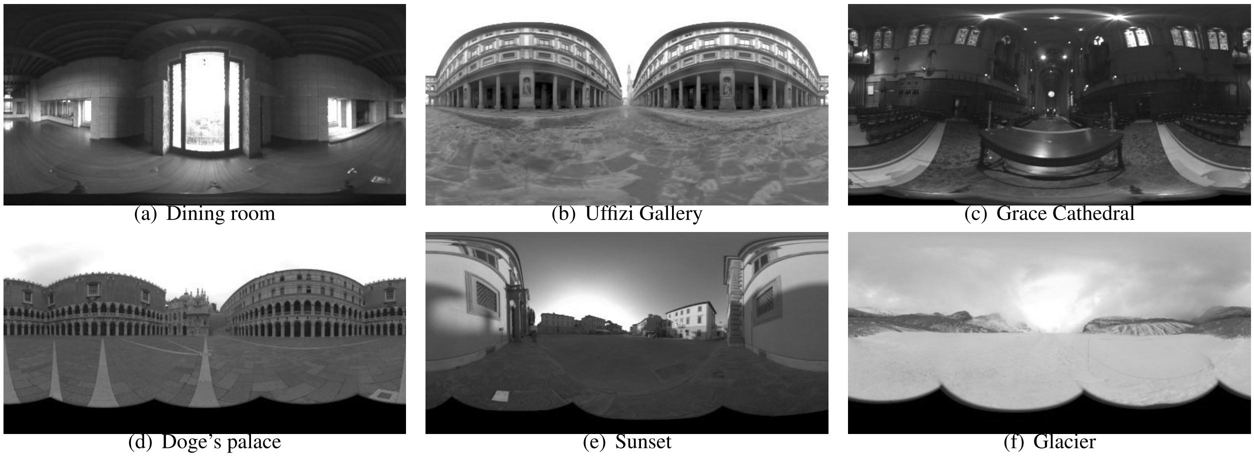

FIGURE 3. The grayscale tonemaps for HDR Panorama photographs of six natural scenes (a) Dining room (b) Uffizi Gallery (c) Grace Cathedral (d) Doge's palace (e) Sunset (f) Glacier (available from: *http://gl.ict.usc.edu/Data/HighResProbes/*).

III. SIMULATIONS

In this section, we systematically investigated the robustness of five metrics mentioned above in simultaneously recovering the light density, direction and diffuseness. These five metrics are based on the use of HDR panoramic maps, the measurements of a cubic meter and the measurements of a tetrahedron meter respectively.

In order to simulate measurements in real complicated lighting environments, we used six HDR Panoramic photographs of the natural scenes (see Figure 3). The cubic and the tetrahedron meter were assumed to be right in the center of each scene. To investigate the robustness of each metric, we simulated 100 postures for each meter by systematically varying the latitude and longitude of the meter with 20° intervals. The illuminance values falling on each face of the cubic and tetrahedron meter were calculated under each posture and each HDR panoramic map. In terms of the cubic meter measurements, we recovered the flux density, direction and diffuseness based on the illuminance on the six faces using both Cuttle's method and Xia's SH-based method. As for the tetrahedron illuminance meter, the low-order properties of light field were also recovered in two ways as described in the previous section. The performance comparisons of these five metrics were given below in detail.

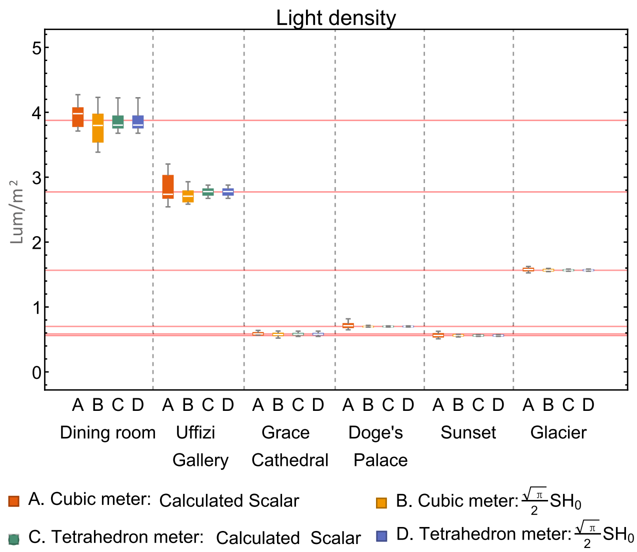

FIGURE 4. Box plot for the recovered light density, obtained from 100 different simulated postures of a cubic meter and a tetrahedron meter. Six HDR panoramic maps were adopted. The horizontal red lines indicate the light density estimated from the full SH decomposition of each HDR panoramic map.

A. SIMULATION RESULTS OF THE LIGHT DENSITY

Figure 4 gives the box plot for the recovered light density obtained from 100 different simulated postures of the cubic meter and the tetrahedron meter. A and B represent the light density estimates based on the cubic meter measurements, with A using Cuttle's method (i.e. illuminance scalar component) and B using Xia's SH-based method (i.e. $\sqrt{\pi}/2$ times of the zeroth-order component of the SH representation of the light field as shown in equation 1). C and D r epresent the light density recovered based on the tetrahedron meter measurements, with C using the average of the four illuminance values and D using the SH fitting method. The horizontal red lines indicate the light density estimated from the first two order SH decomposition of each HDR panoramic map, which is independent of meter postures and is regarded as theoretical light density.

Figure 5 gives the histograms of the ratio between the recovered light density and the theoretical light density for each of the four metrics using meters and for each of the panoramic maps. The more frequencies are distributed around the ratio "1", it indicates the less influence of the meter's postures has on the recovered light density values.

Figure 4 and Figure 5 suggest that, in general, when the cubic meter is used, the SH-based method is less sensitive to the meter's posture than Cuttle's method except for the

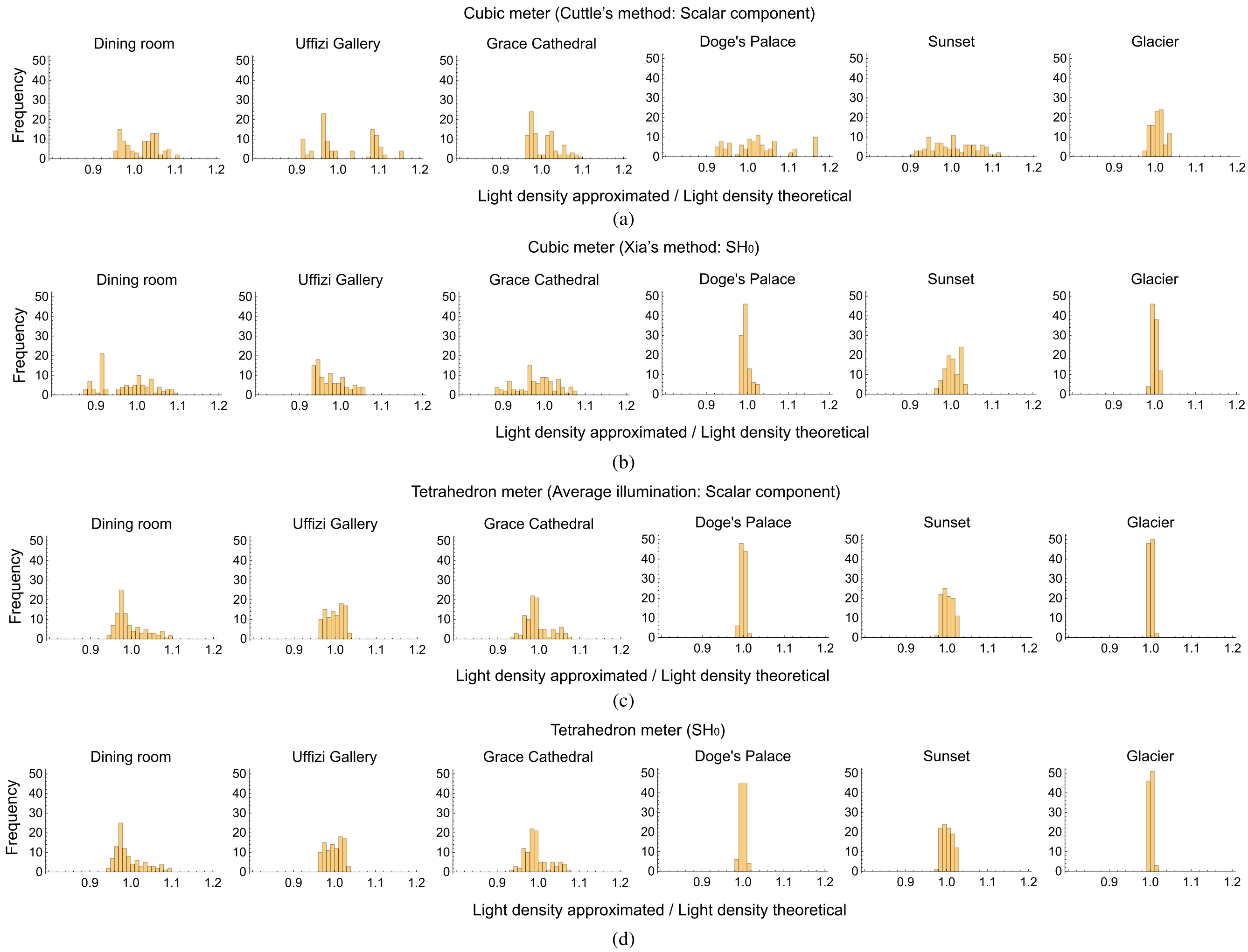

FIGURE 5. Histograms of the ratio between approximated light density and the theoretical light density. The approximated light density values were recovered when using (a) a cubic meter with Cuttle's method, (b) a cubic meter with Xia's method, (c) a tetrahedron meter by averaging the illuminance on the four faces and (d) a tetrahedron meter using the SH fitting method. The theoretical light density values were calculated as $\sqrt{\pi}/2 * SH_0$, where the SH_0 were derived from the zeroth order of the full SH decomposition of each image.

"Dining room" map. Surprisingly, for the tetrahedron meter, the performance of two methods were similar, and they both are more robust than the metrics using the cubic illumination meter. Nevertheless, the recovered light densities are all quite close to the estimates using SH decomposition-based method, which is also called as theoretical ones.

B. SIMULATION RESULTS OF THE LIGHT DIRECTION

Figure 6 shows the box plot for the estimated light vector strength and Figure 7 reveals the estimated directions of the light vectors. Figure 7(a) and (b) shows that the estimated light comes from the rear left for map "sunset", which is consistent with what the map shows in Figure 3(e). The same result is applicable to other maps. It suggests that, based on the measurements on the cubic meter, both Cuttle's physical approximation method and Xia's SH-based method estimate the light vector strength and light vector directions precisely and the results are independent of the cubic meter's postures. However, the results based on the measurements of the tetrahedron meter in Figure 7(c) and (d) have shown big variances both in the light vector strength estimations and direction estimations. The results indicate that, although the tetrahedron meter allows measuring the light density quite well, it could not measure the light vector robustly.

One step further, comparing Figure 7(c) with (d), it could be noticed that the variance of the recovered light direction using different metrics based on the measurements of a tetrahedron meter has exactly the same pattern. The recovered light vector strength using SH-based method is 1.5 times bigger than that projecting four faces' measurements of a tetrahedron in the Cartesian x, y and z axes, which is shown in 6 as the width difference between the box plots. The difference could be explained that the regular tetrahedron has only four faces but the Cartesian coordinate system has six directions, which is 1.5 times more than that of a tetrahedron.

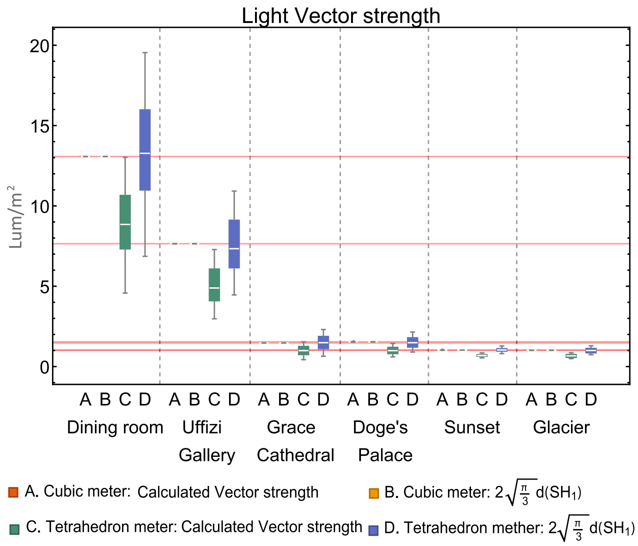

FIGURE 6. **Box plot for the recovered light vector strength obtained from 100 different simulated postures of the cubic and the tetrahedron illuminance meters under six HDR panoramic maps. The horizontal red lines indicate the light vector strength estimates from the full SH representation of each HDR panoramic map.**

Even so, these two metrics have the same function in recovering directions and also light density (see Figure 4 and Figure 5).

C. SIMULATION RESULTS OF THE LIGHT DIFFUSENESS

Since the cubic meter allows measuring the light vector accurately but not the illumination scalar, the variance in the estimates of the light diffuseness using a cubic meter are primarily determined by the error in the scalar component. We have noticed that the tetrahedron meter allows measuring the scalar component more robustly than the cubic meter and thus a combination of a cubic meter to measure the light vector and a tetrahedron meter to measure the light density is expected to optimize the diffuseness estimates. In Figure 8, this optimized estimate is compared with D_{Cuttle} and D_{Xia} ("0" represents fully collimated light and "1" represents fully diffuse light). As we have expected, the results indicate that the ratio between the vector strength measured using the cubic meter and the scalar component estimated with the tetrahedron meter is indeed less sensitive to the posture variations of the illumination meters. Overall, the spread over the 100 different postures is small and the results indicate that all methods can well be used to measure the diffuseness regarding to human visual system's sensitivity to the light diffuseness [19], [26], [28].

IV. DISCUSSION

To conclude, we did a systematical investigation into the performance of a cubic meter and a tetrahedron meter as well as HDR panoramic map decomposition method in measuring the local light density, direction and diffuseness. Besides the local description of light field, the light distribution in natural spaces shows spatial variations of the ambient, vector and diffuseness (i.e., the so-called global structure of the light field). This kind of variation can be captured using simple cubic measurements, tetrahedron meter measurements or HDR panoramic map shooting and interpolation of these measurements over the space.

We have found that the SH decomposition of HDR panoramic map-based method to simultaneously measure the light density, direction and diffuseness was more robust and it was independent of the postures of the meters used. Taking the measurement of light scalar for example, while other metrics were either a physical approximation of the average illumination on a sphere or an approximate fit of up to the first order of SH decomposition of the light fields, SH decomposition of HDR panoramic map-based method is based on a mathematical description of the physical light distribution in the space. The HDR panoramic maps of real scenes can be taken by first assembling a sequence of exposures into a single HDR image then warp images to panoramic formats through some software (e.g., HDRShop, Photosphere) [5], [10], [14], [23]. However, the scale factor (or named as constant k) between the pixel values of the selected region on the map and its physical luminance measurement still need to be calibrated. For the HDR maps taken in real scenes, the scale factor is related to the characteristic curve of the imaging camera and the imaging parameters [21]. Research on how to measure luminance using HDR images were undergoing, from which the scale factors can be derived [2], [13], [30]. Once the HDR panoramic maps have been calibrated to its real luminance values, the local low-order photometric parameters of light field (i.e. light density, direction and diffuseness) can be calculated immediately.

In the absence of calibrated HDR panoramic maps, the use of cubic or tetrahedron meter could be a direct and convenient way to measure the low-order photometric parameters of light fields. Comparing the performance of cubic illumination meter and tetrahedron shaped meter, it was found that tetrahedron meter gave more robust results regarding to the measurement of light density. However, the cubic meter performed better than the tetrahedron meter in the measurement of light direction (i.e. both light vector and light vector strength). It was found that both metrics based on cubic meter measurements gave accurate result of light vector and light vector strength no matter how the meter was located. This finding was not mentioned before in any previous work. As already known, the light diffuseness can be calculated as the ratio between light vector strength and light density. It indicates that all the variations in the measurement of the light diffuseness in previous research were derived from the variations in the measurement of light density [18], [25]. Thus, this study provides one solution for more robust measurement of light diffuseness, that is the ratio between the vector strength estimated with the cubic meter and scalar component measured using tetrahedron meter.

Nowadays, smart phones can function as light meters either by using their built-in cameras plus a diffusing dome such

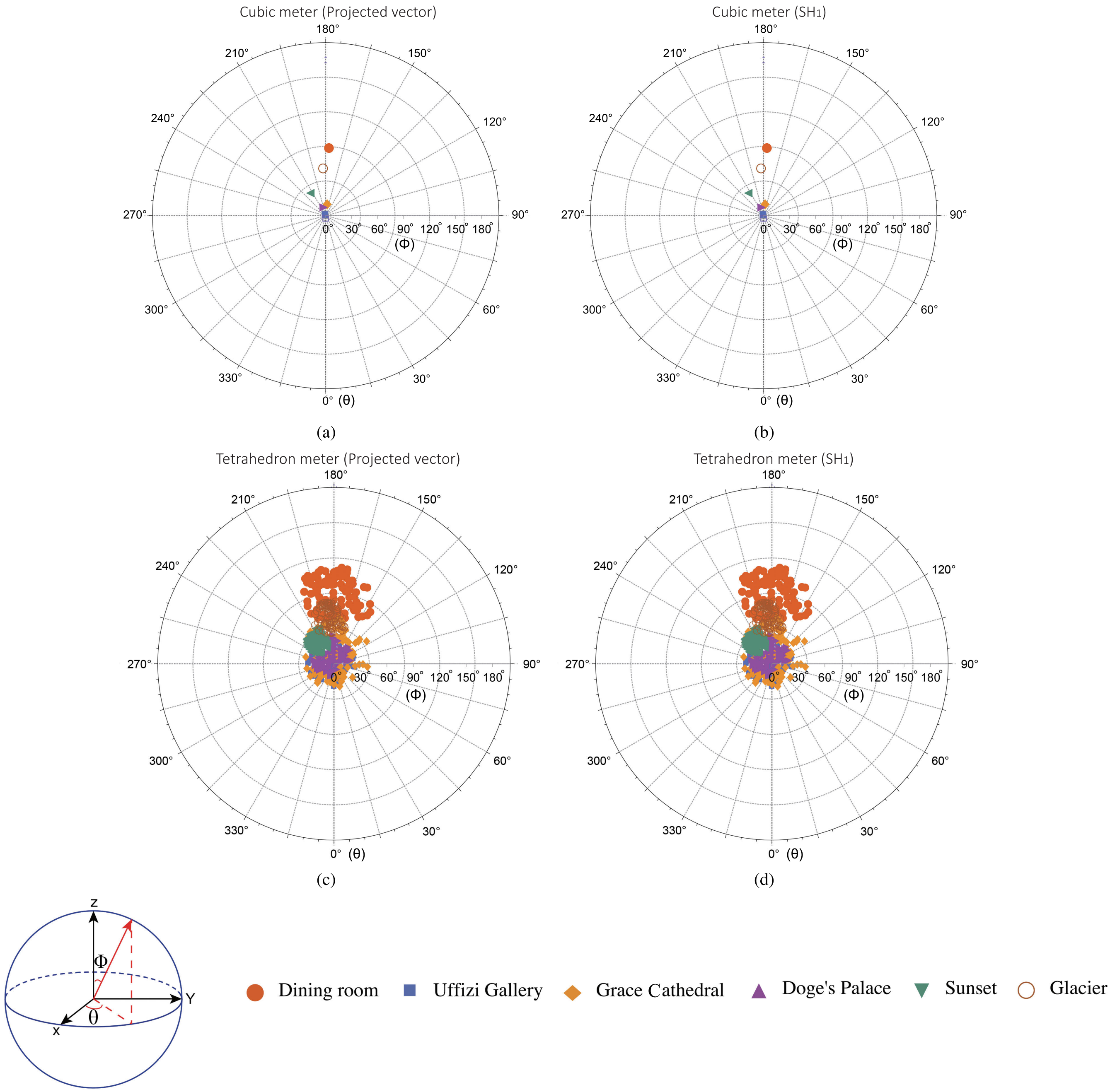

FIGURE 7. Polar plots for the recovered light direction obtained from 100 simulated postures of the cubic and the tetrahedron illuminance meters under six HDR panoramic maps, when using (a) a cubic meter and Cuttle's method, (b) a cubic meter and Xia's method, (c) a tetrahedron meter and projection method and (d) a tetrahedron meter and the SH fitting method.

as the Luxi (fits over the phone's camera) or by using a plug-in device (e.g. Lumu, a built-in sensor and diffusion dome that plugs in the headphones jack and measures the light level directly) [1]. With the help of the phone's position and orientation sensors or in the favor of small tools as shown in Figure 1(a) and Figure 2, a smart phone-based cubic meter or tetrahedron meter can be easily built. Alternatively, HDR panoramic map capturing applications can be developed on smart phones. Then, light direction and diffuseness can be calculated directly and the light density can be got with the calibration information of this smart phone. The global structure of the light field can then be obtained by measuring the low-order photometric parameters at several points of the space and visualizing the interpolated data. We believe that the development of such an app for smart phones could serve as a tool to provide insights into the spatial and form-giving character of light in 3D space for people who are interested in lighting.

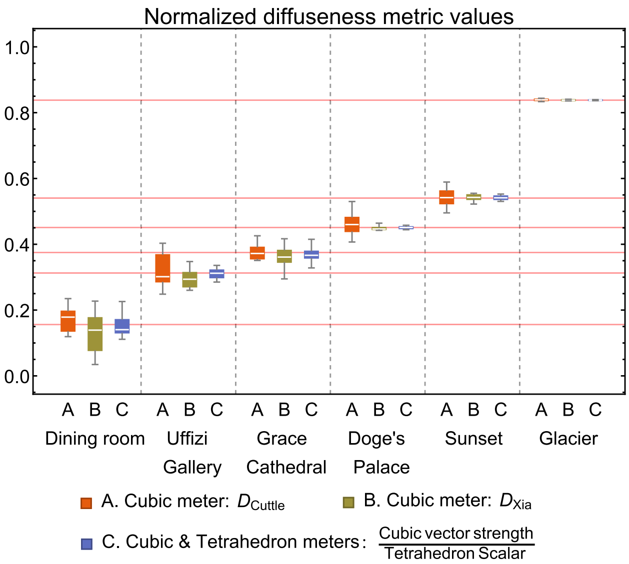

FIGURE 8. Box plot for the normalized light diffuseness obtained from 100 different simulated postures of the cubic and the tetrahedron illumination meters under six HDR panoramic maps. The horizontal red lines indicate the normalized light diffuseness estimated from the full SH representation of each HDR panoramic map.

V. CONCLUSION

In this paper, a systematical comparison of the performance of five metrics in measuring the local light density, direction and diffuseness was conducted. Within these metrics, two were based on the use of a cubic illumination meter, two using a regular tetrahedron shaped illumination meter and one based on SH decomposition of HDR panoramic maps. All the performance of five metrics were simulated under six HDR panoramic maps of natural scenes mimicking real complicated lighting environments. The results indicate that the measurement of low-order photometric parameters of light field (i.e. light density, direction and diffuseness) using HDR panoramic map gives the most reliable results but require calibration when measuring light density. The tetrahedron meter gives more robust results in the measurement of light density while the cubic meter can give precise measurement of light direction (i.e. both light vector and light vector strength). Furthermore, this study shows that the ratio between the vector strength measured with a cubic meter and scalar component measured with a tetrahedron meter gives more robust measurement of light diffuseness. Based on the findings of this research and with the development of mobile computing technologies and the development of HDR panoramic map capturing applications, it can be expected that the mobile phone can function as light meters and provide insights into the spatial and form-giving character of light in 3D space in the near future.

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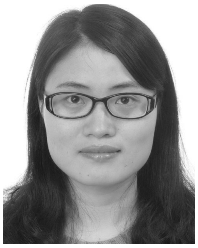

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