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*Published in:*
Photogrammetric Journal of Finland

*DOI:*
10.17690/017252.1

Published: 07/12/2017

*Document Version*
Publisher's PDF, also known as Version of record

*Please cite the original version:*
Kurkela, M., Maksimainen, M., Vaaja, M., Virtanen, J-P., Kukko, A., Hyyppä, J., & Hyyppä, H. (2017). Camera preparation and performance for 3D luminance mapping of road environments. *Photogrammetric Journal of Finland, 25*(2), 1-23. [1]. https://doi.org/10.17690/017252.1

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CAMERA PREPARATION AND PERFORMANCE FOR 3D LUMINANCE MAPPING OF ROAD ENVIRONMENTS

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ABSTRACT

Road lighting measurements are executed with stationary imaging luminance photometry. In these measurements, a digital camera is utilized to create 2D luminance data maps of the scenery. We consider the third dimension to be a meaningful advancement for luminance data presentation and analysis. Hence, we present the preparation for a digital camera in order to use it as an imaging luminance photometer combined with a laser scanning system. The target area of use for our measuring system is the night-time road environment. We assessed the limiting factors when integrating luminance photometry into laser scanning systems. We achieved the initial luminance data and 3D point cloud integration for terrestrial laser scanning (TLS) and mobile laser scanning (MLS) systems. In stationary luminance measurements, the target luminance range was achieved. For mobile measurements, the target luminance range was compromised. The mobile measurement luminance range was limited because a long exposure time could not be used. A short exposure time was compensated for by increasing the sensor sensitivity, which reduced the signal-to-noise ratio. In mobile measurements, the luminance range can be extended towards the low end only by reducing the movement velocity or by accepting more motion blur in the measurements.

1. INTRODUCTION

Measurements of road and street lighting conditions are used to evaluate the performance of the lighting installation. The luminance of road surfaces, markings, and furniture can be investigated. Luminance measurements are also necessary for verifying the performance of installations in maintenance and for comparing different road lighting installations for cost and functionality.

Luminance photometry can be applied when designing and maintaining lighting installations. It can also be used to verify the results of lighting simulations (Houzer et al., 1999). Luminance describes the luminous intensity emitted from a particular area in a given direction (Electropedia, 2017). The SI unit for luminance is candela per square meter (cd/m²). Luminance is perceived as the brightness of a surface or a light source. Spot luminance meters can be used to measure luminance values of individual confined areas of a surface, but they are not suitable for measuring the luminance distribution in large areas (Ekrias et al., 2008) or for studying the luminance distribution in a complex environment.
At the present time, two-dimensional false-color imagery is the most common way to illustrate and analyze the results in imaging luminance photometry. We consider the third dimension to be a meaningful improvement for luminance data presentation and analysis. Moreover, we consider the luminance data will extend the analysis potential of laser-scanned road environments. Examples of combining imaging sensors with 3D data can be found for thermal images (Previtali et al., 2012) and luminance images (Vaaja et al., 2015). Furthermore, 3D modeling and analysis have been applied with a sunlight factor (Zhang et al., 2014). However, the mentioned articles do not thoroughly describe the camera calibration procedure.

The national regulations for road lighting often follow a standardized guideline such as CEN/TR 13201:2015 (CEN/TR, 2015) and ANSI/IES RP-8-14 (IESNA, 2000). These standards determine the luminance level needed to guarantee the visibility and safety of a certain road class. The CEN/TR 13201:2015 standard categorizes the driveways for motorized traffic into six classes, M1–M6, according to their attributes (CEN/TR, 2015). These attributes include traffic volume and junction density. For the most demanding class, M1, the requirement for the average luminance level, $\bar{L}$, is 2.0 cd/m$^2$. For the least demanding class, M6, the $\bar{L}$ requirement is 0.30 cd/m$^2$. Moreover, luminance uniformity requirements allow local luminances to be moderately higher or lower than the required average luminance. Hence, to be applicable to luminance measurements according to CEN/TR 13201:2015, the system should perform for luminances ranging from at minimum 0.10 to 3.0 cd/m$^2$.

Standards regulate the road lighting measurement procedure (SFS-EN, 2014). The state-of-the-art method for road lighting measurement is stationary imaging luminance photometry (Eloholma et al., 2001; Cai and Li, 2014). A calibrated digital camera can be utilized to produce luminance measurement images (Anaokar and Moeck, 2005; Wüller and Gabele, 2007; Meyer et al. 2009; Hiscocks and Eng, 2017). Imaging luminance measurements allow detailed 2D analyses of luminances in road environment scenes.

There are commercial imaging luminance photometers or luminance cameras available such as the TechnoTeam ‘LMK mobile air’ (LMK, 2017). The ‘LMK mobile air’ can be utilized to measure luminance values of a measurement field from a stationary position. The raw images taken on the measurement area are then interpreted as luminance maps, using the designated analysis software LMK LabSoft. The ‘LMK mobile air’ imaging luminance photometer is in practice a commercial digital reflex camera, the Canon EOS 70D. The manufacturer, TechnoTeam, has calibrated the sensor of a digital camera and the vignetting of the optics to create a commercial luminance camera. In order to extend the luminance range, high dynamic range (HDR) photography is applied. In HDR photography, several images are taken from the same position using different exposure times. However, without the geometric calibration, commercial luminance cameras cannot be integrated into a laser scanning system.

Currently, the most advanced and accurate systems for measuring the 3D geometry of road environments are terrestrial laser scanners (TLS) and mobile laser scanners (MLS). Figure 1 illustrates a 3D point cloud scanned with an MLS. In addition, Figure 1 presents a luminance camera and a false-colored luminance data map conceptualization in the camera’s viewfinder.

TLS is a widely used 3D measurement technology already utilizing methods of automatic registration (Guarnieri, 2011), and its applications include material classification (Costantino and Angelini, 2013b) and digital terrestrial model creation (Costantino and Angelini, 2013a). In recent years, MLS has provided efficient and versatile applications for collecting 3D data for built and natural environments. MLS is a surveying technique that combines laser scanning for distance
measurement, global navigation satellite systems (GNSS) for determining position, and an accurate inertial measurement unit (IMU) for measuring 3D orientation. In particular, MLS has been applied to mapping and monitoring roads and city environments. It has been used for extracting various features, such as building façades, road surfaces, tunnels, railway tracks, poles, luminaires, and trees (Jaakkola et al., 2008; Lehtomäki et al., 2010; Rutzinger et al., 2010; Jochem et al., 2011; Manandhar and Shibasaki, 2002; Yang et al., 2012; Arastounia et al., 2013; Kaartinen et al., 2013; Wu et al., 2013; Puente et al., 2014; Cabo et al., 2016). Data from imaging sensors can be fused with MLS or other laser scanning data sets (Lin et al., 2011). An example of hyperspectral measurement combined with laser scanning has been presented by Puttonen et al. (2011), and thermal imaging by Jaakkola et al. (2010). A typical implementation is to integrate digital cameras on the same platform with a laser scanner for obtaining color values. For combining luminance imaging with a 3D point cloud for analyzing luminance on the road surface, a TLS has been used (Vaaja et al., 2015). However, TLS is a time-consuming method for measuring large road networks.

![Image](image.png)

**Figure 1.** A conceptual image referring to laser scanning and luminance photometry integration. The image illustrates the 3D point cloud scanned with a laser scanner. Furthermore, the false-colored area in the luminance camera’s viewfinder screen represents the luminance map captured.

As the MLS is performed from a moving platform, the movement has to be taken into account when using the imaging sensor. In practice, the exposure time of the imaging sensor has to be short enough to avoid motion blur in the images, and the triggering time of the sensor has to be known to resolve its position on the platform’s trajectory. In addition, for accurately integrating imaging measurements to 3D point cloud data sets, the internal geometry of the camera used to obtain the images has to be known. This can be solved with an interior camera calibration (Fryer and Brown, 1986).

On a moving platform, luminance measurement from HDR images becomes an unfeasible option, as several exposures are needed to produce the HDR image. If we are to perform an imaging luminance measurement using a digital camera on a moving platform, this has to be done from individual images taken with sufficiently short exposure times, depending on the speed of the moving platform. In low-light conditions, this dictates the use of a high sensitivity setting in the sensor. In a digital camera, high sensitivity means a high ISO value.
We present the preparation of luminance photometer for integration into TLS or MLS systems. The applied MLS platform can range from an unmanned aerial vehicle (UAV) to car driving on the highway (Jaakkola et al., 2010; Kukko et al., 2012) or even to a future tandem mobile UAV collaborative system (Lin et al., 2013). Additionally, future autonomous cars will have both MLS and camera instruments onboard allowing the road luminance mapping. Therefore, the luminance measurement has to be applicable in both stationary platforms (with long exposure times) and especially moving platforms (with short exposure times). More specifically, both are to be used in road environments at night, with typical luminances of the measurement field being 0.1–3.0 cd/m². These luminance values are the average luminances adjusted with the uniformity requirements defined for the motorized driveway classes M1–M6 (CEN/TR, 2015). We present the luminance calibration of the camera for the intended luminance levels. We also apply internal camera calibration to undistort luminance images for point cloud coloring. Finally, we evaluate the performance of the systems for measuring the luminance range of 0.1–3.0 cd/m². Furthermore, we assess the limitations in low luminance level mobile luminance measurement.

2. MATERIALS AND METHODS

2.1 Methods for Luminance Camera Calibration

In this study, we present a workflow of methods that prepares a camera for coloring 3D point clouds with luminance data. Figure 2 describes the methods that include the camera calibration and the image processing needed for the data integration.

![Calibration Workflow Diagram]

Figure 2. Calibration and image processing workflow for creating luminance point clouds.

This article focuses on the preparation of the camera, using the processes above the dashed line in Figure 2. The preparation is divided into three parts: luminance calibration of the sensor, vignetting calibration of the camera system, and geometric calibration of the camera. Luminance and vignetting calibrations are needed in order to capture precise luminance measurements. Geometric calibration is needed in order to register the luminance data to the point cloud.
The results of field measurements are briefly presented in this study. Coloring the point cloud with luminance images is shown in Figure 2 under the dashed line.

### 2.2 Reference Luminance Source Measurements

To produce a controlled luminance for acquiring calibration images, an Optronic Laboratories, Inc., model 455–6–1 reference luminance source was used (Figure 3). The device contains a stable light source, a dimming aperture, and an integrating sphere. To determine the ratio of absolute luminance of the reference source and digital values of the camera with specific exposure settings, a set of images with known luminance was acquired. We performed the luminance calibration separately for stationary and mobile measurement purposes.

![Figure 3. An Optronic Laboratories, Inc., model 455-6-1 reference luminance source.](image)

The luminance value of the reference luminance source was measured using a Konica Minolta CS-2000 spectroradiometer. The measuring solid angle was 1°. A neutral-density filter was used in front of the exit port in order to obtain small luminance values more accurately.

### 2.3 Camera Equipment Calibrated

The cameras being calibrated were a Nikon D800E a conventional digital single-lens reflex (DSLR) camera and a Ladybug3 panoramic camera system (Figure 4).

![Figure 4. Nikon D800E camera and Ladybug3 panoramic camera system.](image)
For stationary imaging, we used the Nikon D800E camera with a Nikkor AF-S 14–24mm f/2.8G lens. The Nikon D800E has a low noise and high dynamic range 36.3-megapixel sensor and the ability to capture HD video. The zoom and focus of the Nikkor lens were locked at 14mm to minimize changes to the internal camera calibration. An aperture of f/5.6 was selected for an optimal sharp image without diffraction and less vignetting. For an optimal signal-to-noise ratio, the ISO sensitivity value of 100 was chosen.

For moving platforms, we selected the Nikon D800E and the Ladybug3. The Nikon D800E had the same lens as with the stationary imaging case. An f/2.8 aperture and 3200 ISO were applied to enable a 1/125 second shutter speed for the Nikon D800E. When recording sequences of images in the NEF format, only 0.5 frames per second (FPS) is possible, which sets limits to the driving speed. The Ladybug3 has six 2.0-megapixel 1/1.8” CCD sensors with 3.3 mm focal length lenses, which covers 80% of the full sphere, and it enables uncompressed imaging at 6.5 FPS. For photogrammetric purposes, the Ladybug3 fixed focus camera had been pre-calibrated, and it can be synchronized to an external trigger.

2.4 Luminance Calibration

The calibration was performed with the same exposure settings used in the field measurements. The aperture, shutter speed, and ISO value were fixed. We aimed to use the lowest possible ISO value of the sensor to minimize noise. For stationary imaging, we used ISO 100 because long exposures were possible using a tripod. ISO 3200 was selected for mobile measurement purposes with Nikon cameras to be able to use an exposure time of 1/125 s. With a mobile measurement velocity of 10 m/s, an exposure time of 1/125 s causes the measurement averaging over 0.08 m in the direction of movement. In a conventional luminance measurement, the longitudinal distance between two measurement points is rarely less than 1.0 m. Hence, a longitudinal motion blur of 0.08 m or less can be considered acceptable for mobile luminance measurements. For the Ladybug3 camera, the greatest gain value (18 dB) was used. To capture the highest quality image, the Nikon D800E was set to produce 14-bit NEF images.

2.4.1 Image Processing for Luminance Calibration

Images produced by the Nikon D800E were stored in the raw image format, which needed to be converted to the TIF format for post-processing. The raw image conversion was performed with the dcraw decoding program (DCRaw, 2017). In order to produce the highest image quality for post-processing, raw images were converted to linear 16-bit TIF images in the camera’s own color space setting. The Ladybug3 recorded uncompressed files that were converted to the linear 8-bit TIF format.

An area of 100×100 pixels for the Nikon D800E and 10×10 pixels for the Ladybug3 were selected for luminance calibration. The center of each selected area is on the principal point of the image covering the exit port of the reference luminance source. The median RGB channel values from the areas were stored with a reference luminance source value. The median value of each channel was used to perform noise reduction on the image. Theoretically, vignetting is present also in the small center 100×100 pixel area of the Nikon D800E sensor. However, this light falloff is miniscule and therefore ignored in the luminance calibration. Vignetting for the whole sensor area is covered in Section 2.5.
2.4.2 Computation of Luminance Using Digital Pixel Values

The images captured by a digital camera are stored as digital pixel values with RGB channels. The digital camera can be used as an imaging luminance photometer by calibrating it to a reference light source. In other words, the pixel values are directly correlated to the known luminance (cd/m²) levels (Vaaja et al., 2015; Ambekar et al., 2017; Hiscocks and Eng, 2017). Equation 1 shows a correlation for estimating the luminance of a digital pixel value

\[ K = \frac{N_d f_s^2}{L_s t S_{ISO}} \]  

(1)

where \( L_s \) indicates the luminance, \( N_d \) indicates the digital pixel value in the raw image obtained with Equation 2, \( f_s \) is the aperture, \( K \) is the calibration constant for the camera, \( t \) is the exposure time in seconds, and \( S_{ISO} \) is the ISO value. The \( N_d \) value was obtained using Equation 2 defined by the IEC standard

\[ N_d = 0.2162R + 0.7152G + 0.0722B \]  

(2)

where \( R, G, \) and \( B \) indicate the digital values for the individual red, green, and blue channels captured by the camera (IEC, 1999). Applying Equation 2 to a digital image, the relative luminance values were obtained for each RGB pixel. With the absolute luminance value of the image being known, the linear ratio between relative and absolute luminance values was identified. The ratio and Equation 2 were then used to interpret images taken with the calibrated camera as luminance maps.

2.4.3 Luminance Calibration for Stationary Measurements

To produce low luminance values corresponding to night-time road conditions, a neutral density (ND) filter was used in front of the exit port of the luminance source’s integrating sphere. The transfer ratio of the ND filter was measured using an ‘LMK mobile advanced’ imaging luminance photometer and found to be 1/41.8 (Inanici, 2006). After this, a series of 44 images of the ND-filtered reference luminance source was taken with the Nikon D800E. The lens aperture was f/5.6, exposure time 8 s, and ISO value 100 when the luminance calibration was performed for stationary measurements. It was found that with these exposure settings, the maximum measurable luminance value was 2.88 cd/m² because with greater values the R-channel reached its overexposure limit. The luminance source was adjusted to 44 different luminance levels ranging from 0.003 to 2.88 cd/m². The median RGB channel values from an area of 100×100 pixels in the center of the image covering the exit port of the luminance source were used in calibrating the camera.

2.4.4 Luminance Calibration for Mobile Measurements

For measurements on mobile platforms, a lens aperture of f/2.8, an exposure time of 1/125 s, and an ISO value of 3200 were used when the luminance calibration was performed for the Nikon D800E camera. A series of ten images of the reference luminance source was taken. The luminance source was adjusted to ten different luminances: 0.06, 0.12, 0.23, 0.44, 0.89, 1.77, 3.52, 7.00, 14.01, and 27.97 cd/m². The median RGB channel values from an area of 100×100 pixels in the center of the image covering the exit port of the luminance source were used in calibrating the camera. For the Ladybug3, the reference luminance source was adjusted to eleven luminances: 0.06, 0.12, 0.23,
0.45, 0.99, 1.96, 3.95, 4.76, 5.97, 7.22, and 8.63 cd/m². The median RGB channel values from an area of 10 × 10 pixels in the center of the image covering the luminance source’s exit port were cropped for calibration.

2.5 Vignetting Correction

Vignetting gives the appearance of a radial light falloff from the principal point towards the edges of an image. Usually the vignetting effect is stronger when using a wide-angle lens and a wide aperture. The reduction in the light transmission can be 2 to 3 aperture f-stops. Therefore, vignetting correction is essential (Hiscocks and Eng, 2017). Using a perfectly uniform, diffuse, and large luminance source, obtaining the vignetting correction matrix would be simple. However, a large, ideally uniform luminance source is more a theoretical than a practical device. Therefore, it is more pragmatic to solve the vignetting for example by using a small diameter luminance source in a set of locations within the camera’s field of view or a large diameter luminance source with its exit port covering the camera’s full field of view (Inanici, 2006; Cai and Chung, 2011; Lu et al., 2016; Mead and Mosalam, 2017). Alternatively, vignetting information can be extracted from a set of images or a single image by applying an algorithmic method (Goldman and Chen, 2005; Zheng et al., 2008; Kim and Pollefeys, 2008; Zheng et al., 2009). Moreover, vignetting can be calibrated utilizing the checkerboard pattern that is used when calibrating geometric distortion (Inanici, 2006).

Furthermore, vignetting correction can be obtained utilizing a near-uniform, near-Lambertian surface (Kelcey and Lucieer, 2012). In this study, a convenient approach to create a near-uniform, near-Lambertian luminance surface was utilized. The light source was a clear blue southwestern sky with the sun in the northeast. An acrylic diffuser was positioned 5 cm from the camera optics, and a series of 43 images was taken while the camera was rotated radially 360°. Next, an average of 43 images was calculated for each pixel in order to create a vignetting model image. The vignetting model was verified by utilizing it on a set of images of a reference luminance source in a set of locations within the camera’s field of view. Vignetting calibration was only performed for the Nikon D800E, as the Ladybug3 was pre-calibrated by the manufacturer.

2.6 Geometric Distortion

Our camera calibration considers the most common form of lens aberrations, namely geometric distortion and lateral chromatic aberration (Brown, 1971; Fryer and Brown, 1986; Zhang 2005). For luminance calibration, chromatic aberration is not a remarkable component since the source luminance is uniform. However, for luminance images captured in the field, the lateral chromatic aberration correction should be considered. This is especially recommended when image acquisition is done in high-contrast scenes with ultrawide-angle lenses.

For the Nikon D800E, the Camera Calibration Toolbox for Matlab® by Jean-Yves Bouguet was applied to geometric distortion for interior orientation (Bouguet, 2017). The Ladybug3 camera was pre-calibrated by the manufacturer.

2.7 Integration of luminance values with 3D point clouds

Considering data fusion, both 3D point clouds and luminance images need to be registered in the common coordinate frame. Typically, the 3D point cloud is colored with RGB values taken with a digital camera that is often rigidly integrated with a laser scanner. By using luminance and geometric calibrations for images, the RGB values are converted to luminance values, and the 3D point cloud is presented with calibrated luminance images. The TLS point cloud data was colorized
using the image data captured with the Nikon D800E camera. Image data was acquired from the same locations using the same tripod setup as with the TLS scans. A method for collecting and integrating these terrestrial data sources is presented in a study by Vaaja et al. (2015). For a demonstration of a luminance-colored MLS point cloud, we used the Trimble MX2 mobile mapping system, where the Ladybug3 panoramic camera is rigidly integrated into the system. A 800 m urban road section was driven in both directions. The 3D data consisted of 40 million points, and panoramic images were taken at 2-second intervals. For both demonstrations, the data was collected under night-time road and street environment lighting conditions.

3. RESULTS

3.1 Repetition Test for Luminance Calibration

The uncertainty related to the luminance calibration was examined with a repetition test. Using the Nikon D800E, an image of fixed reference luminance value was taken ten times repeatedly. Exposure time was 1/320 s, aperture f/5.6, and ISO 100. A short exposure time of 1/320 s was chosen to especially investigate the randomness related to the shutter action. Table 1 shows the ten median values of the B, G, and R channels in a 100×100 pixel area within the reference luminance source. In addition, Table 1 lists the relative luminance values obtained by applying Equation 2 to the B, G, and R values. On the bottom, Table 1 shows the variation range of 16-bit values for each channel and the relative luminance and the ratio between the variation range and the whole dynamic range. Table 2 shows similar values as Table 1, but for a single pixel (5000th) in the center of the 100×100 pixel area. Hence, Table 1 presents the uncertainty of shutter action and Table 2 presents the noise of the single pixel.

In relative luminance values, a single pixel value variation range is almost ten-fold compared to the range of 100×100 pixel area median relative luminance values. Using the median pixel values of the 100×100 pixel area should filter out the noise on the sensor. Yet there is a 0.07% relative variance range in the set of ten images, and the relative standard deviation of relative luminances was 0.03%. We consider two possible sources for this uncertainty: inconsistency in the amount of time the shutter is open during the capture, and faint flicker in the reference luminance source.

| Image        | B    | G    | R    | relative L |
|--------------|------|------|------|------------|
| _DSC7838.tiff | 4923 | 10072| 18482| 11554.74  |
| _DSC7839.tiff | 4925 | 10072| 18491| 11556.83  |
| _DSC7840.tiff | 4932 | 10080| 18509| 11566.95  |
| _DSC7841.tiff | 4933 | 10088| 18504| 11571.67  |
| _DSC7842.tiff | 4939 | 10100| 18522| 11584.57  |
| _DSC7843.tiff | 4936 | 10092| 18516| 11577.34  |
| _DSC7844.tiff | 4948 | 10112| 18566| 11603.32  |
| _DSC7845.tiff | 4930 | 10094| 18545| 11584.60  |
| _DSC7846.tiff | 4944 | 10114| 18561| 11603.38  |
| _DSC7847.tiff | 4941 | 10111| 18556| 11599.93  |
| range        | 24   | 42   | 84   | 48.57      |
| range / bits | 0.04%| 0.06%| 0.13%| 0.07%      |
### Table 2. Values for the 5000th pixel of B, G, and R channels in the selected 100×100 pixel area.

| Image               | B    | G    | R    | relative L   |
|---------------------|------|------|------|--------------|
| _DSC7838.tif        | 4837 | 9912 | 18209| 11375.08     |
| _DSC7839.tif        | 4965 | 10044| 18645| 11572.99     |
| _DSC7840.tif        | 4850 | 9960 | 18632| 11501.80     |
| _DSC7841.tif        | 4957 | 10068| 18518| 11562.12     |
| _DSC7842.tif        | 4942 | 10192| 18614| 11670.48     |
| _DSC7843.tif        | 5000 | 10124| 18401| 11579.98     |
| _DSC7844.tif        | 5079 | 10232| 18570| 11699.46     |
| _DSC7845.tif        | 5162 | 10288| 18651| 11763.02     |
| _DSC7846.tif        | 4990 | 10124| 18529| 11606.93     |
| _DSC7847.tif        | 4983 | 10272| 18740| 11757.90     |
| range               | 325  | 376  | 531  | 387.94       |
| range / bits        | 0.50%| 0.57%| 0.81%| 0.59%        |

#### 3.2 Luminance Calibration for Stationary Measurements

Stationary measurements allow the use of long exposure times. Hence, an ISO 100 value can be used for an optimized signal-to-noise ratio. In addition, we can capture several luminance measurements and combine them into one high dynamic range luminance map. Here, we concentrate on the low end of the important luminance range in road lighting measurements (0.1–3.0 cd/m²). Stationary measurement calibration was performed for the Nikon D800E camera, as described in Section 2.4.3.

In order to find the calibration constant, we compared the reference luminance values to the respective linear 16-bit relative luminance values. The 16-bit relative luminance values were obtained by applying Equation 2 to the median B, G, and R values in the 100×100 pixel area. The 16-bit relative luminance values ranged between 29.99 and 32,253.80.

Now the luminance calibration constant is the average slope when the reference luminance values are presented as the function of the Nikon D800E relative luminance values. Figure 5 demonstrates the calibration constant acquisition.

The average among the slopes between every two adjacent data points was 8.96×10⁻⁵. This is the luminance calibration constant for the Nikon D800E used in this study. Table 3 presents the Nikon D800E relative luminance 16-bit values as a function of absolute luminances of the reference luminance source. In addition, Table 3 shows the minimum and the maximum values, and the standard deviation for each 100×100 pixel data set. When measuring low luminances, the signal-to-noise ratio is the poorest.

Next, the Nikon D800E relative luminance 16-bit values were multiplied by the calibration constant to obtain the absolute luminance values measured with the Nikon D800E. The relative differences of the reference luminance values and respective absolute luminance values measured with the Nikon D800E ranged between 0.23% and 13.63%.

The average relative difference between the reference luminance values and the absolute luminance values measured using the Nikon D800E was 1.91%. As expected, the relative difference was the greatest for the lowest measured luminances. For stationary measurements, the usable single
measurement low-end luminance range was 0.01–2.88 cd/m². This is sufficient for road environment luminance measurements (CEN/TR, 2015). Furthermore, HDR measurements are possible for stationary measurements. Hence, the luminance range can be extended upwards.

Figure 5. The successive reference luminance values presented as a function of the respective Nikon D800E relative luminance values. The red dots are the data set. The black line is the linear function \( y = 0.0000896x \).

Table 3. Mean, minimum and maximum values, and standard deviation for the data sets per reference luminance value. Data from a Nikon D800E luminance calibration for stationary measurements; ISO 100.

| Mean   | Min  | Max    | Std   | Luminance (cd/m²) |
|--------|------|--------|-------|-------------------|
| 30.237 | 1.946| 59.440 | 6.856 | 0.003             |
| 37.769 | 11.559| 67.327 | 7.321 | 0.004             |
| 48.268 | 11.242| 81.869 | 7.891 | 0.005             |
| 59.686 | 25.863| 97.010 | 8.613 | 0.006             |
| 75.185 | 41.314| 115.076| 9.315 | 0.007             |
| 88.554 | 51.433| 129.866| 9.981 | 0.008             |
| 109.503| 70.610| 158.880| 10.961| 0.010             |
| 127.244| 51.923| 175.818| 11.649| 0.012             |
| 147.163| 101.496| 195.382| 12.449| 0.014             |
| 165.442| 116.031| 215.043| 12.833| 0.015             |
| 196.073| 145.313| 250.948| 14.031| 0.018             |
| 224.419| 174.987| 275.615| 14.984| 0.020             |
| 249.079| 189.583| 304.494| 15.713| 0.023             |
| 289.194| 213.347| 357.716| 16.893| 0.026             |
| 335.004| 271.258| 406.238| 17.823| 0.030             |
3.3 Luminance Calibration for Mobile Measurements

The luminance calibration for mobile measurements was similar to the calibration for stationary measurements in Section 3.2. For mobile measurement, using a long exposure time is not possible because a long exposure would cause motion blur. Thus, the exposure time must be shortened. Shortening the exposure time makes it necessary to increase the ISO value and the aperture in order to perform at the same low luminance levels as stationary measurements. Increasing the ISO value or gain lowers the signal-to-noise ratio, and a larger aperture makes the measurement more vulnerable to lens vignetting errors.

The Nikon D800E and Ladybug3 were calibrated as described in Section 2.4.4. The results in Figure 6 show the linear ratios between the digital pixel value presented in 16 bits and the absolute luminance values for the Nikon D800E and the Ladybug3 panoramic camera system. On the Ladybug3, only one of the sensors was calibrated.
When measuring with the Nikon D800E using an ISO 3200 value, or with the Ladybug3 using a gain setting of 18 dB, the signal-to-noise ratio for low luminances becomes poor. This reduces the effective dynamic range in mobile luminance measurements. Tables 4 and 5 present the calibration values for the Nikon D800E and the Ladybug3, respectively.

It is evident that the low signal-to-noise ratio reduced the reliability of measuring luminances lower than 0.45 cd/m². For mobile measurements, the usable luminance range was 0.44–27.97 cd/m² when using the Nikon D800E, and 0.99–8.63 cd/m² when using the Ladybug3.

Table 4. Mean, minimum and maximum values, and standard deviation for the data sets per reference luminance value. Data from a Nikon D800E luminance calibration for mobile measurements; ISO 3200.

| Mean    | Min  | Max      | Std    | Luminance (cd/m²) |
|---------|------|----------|--------|-------------------|
| 89.942  | 0.000| 865.652  | 74.254 | 0.057             |
| 150.131 | 0.000| 1248.977 | 93.491 | 0.115             |
| 274.151 | 0.000| 1216.391 | 118.853| 0.229             |
| 540.789 | 84.226| 1201.548 | 152.056| 0.444             |
| 1083.774| 358.027| 1914.933 | 197.971| 0.885             |
| 2185.626| 1166.062| 3281.687 | 271.265| 1.766             |
| 4269.269| 2831.298| 5613.327 | 354.074| 3.519             |
| 8390.707| 6627.597| 10054.968 | 506.139| 7.000             |
| 16824.984| 14426.066| 19287.533 | 705.291| 14.010            |
| 33640.996| 29865.105| 37453.553 | 996.364| 27.970            |
Table 5. Mean, minimum and maximum values, and standard deviation for the data sets per reference luminance value. Data from a Ladybug3 luminance calibration for mobile measurements; gain 18 dB.

| Luminance (cd/m²) | Mean | Min | Max | Std |
|-------------------|------|-----|-----|-----|
|                  | 1.459| 0.000 | 2.866 | 0.685 |
|                  | 1.804| 0.216 | 4.513 | 0.919 |
|                  | 3.653| 0.432 | 6.670 | 1.218 |
|                  | 8.575| 2.012 | 16.273 | 2.351 |
|                  | 19.707| 14.914 | 23.514 | 1.919 |
|                  | 39.767| 31.762 | 47.543 | 3.690 |
|                  | 79.136| 60.382 | 96.632 | 5.889 |
|                  | 96.248| 77.669 | 107.970 | 5.060 |
|                  | 120.207| 104.409 | 139.162 | 6.750 |
|                  | 148.039| 126.857 | 167.844 | 8.023 |
|                  | 174.959| 152.864 | 192.930 | 7.536 |

3.4 Results of Vignetting

The vignetting of the Nikon D800E camera with the Nikkor AF-S 14–24mm f/2.8G lens was measured at f/2.8 aperture and focal length locked at 14 mm. The vignetting was obtained by a series of images of a near-uniform luminance surface, as described in Section 2.5. Figure 7 (a) illustrates the vignetting. Due to vignetting, the responsivity of the camera falls down to 19.4% towards the corner of the sensor. Thus, the radial light falloff is more than two f-stops.

![Figure 7. (a) Vignetting of Nikon D800E with the Nikkor AF-S 14–24mm f/2.8G lens at f/2.8 aperture; (b) Light falloff from 100% to 19.4% illustrated with a 3D plot.](image)

The vignetting result shows that the responsivity of the camera gets smaller toward the edges of the image. Figure 7 (b) visualizes the light falloff from the principal point to the lowest value in each corner. Using our vignetting correction, the vignetting was corrected with a maximum error of 3.8% compared to the luminance reference value of the same pixel.

3.5 Results of Geometric Calibration

The Nikon D800E with a 14–24mm lens was locked at the 14mm focal length, and the lens aperture was fixed at f/2.8. A total of 35 images were used for geometric calibration. We used the nominal 7360×4912 image size. After initialization, the nonlinear optimization was performed. The
parameters for principal distance, principal point, radial distortion coefficients (K1, K2, K3), and decentering distortion coefficients (P1, P2) were solved and are listed in Table 6.

Table 6. Calibration results after the nonlinear optimization step with uncertainties in pixels.

| Parameters          | Values         | Uncertainties |
|---------------------|----------------|---------------|
| Principal distance  | 2956.86184     | ± 9.60000     |
| Principal point x   | 3651.27330     | ± 1.69803     |
| Principal point y   | 2444.74283     | ± 2.48139     |
| K1                  | -0.01967       | ± 0.00049     |
| K2                  | -0.00616       | ± 0.00058     |
| K3                  | 0.00213        | ± 0.00021     |
| P1                  | -0.00004       | ± 0.00006     |
| P2                  | 0.00029        | ± 0.00006     |

The standard deviations of the reprojection error were 0.57184 and 0.56355 pixels in the x and y directions, respectively. The Camera Calibration Toolbox for Matlab® shows the numerical errors of the parameters to be approximately three times the standard deviations. These calibration results are adequate for integrating camera into laser scanning system in terms of geometry. In practice, the erroneously registered luminance value of the 3D point is caused more by the error in the relative orientation between the camera and the laser scanner than by the interior orientation error of the camera. For example, the registration error in the relative orientation between the Nikon D800E and the Faro Focus 3D laser scanner was 4.7 pixels (Vaaja et al., 2015).

### 3.6 Visualizing Luminance Values in 3D point clouds

We introduce the outcome of the luminance map and 3D point cloud integration. Both the stationary and mobile luminance measurements were successfully registered with the respective laser scans. In this study, the integrations are not explained thoroughly, as this article focused mainly on the calibration methods. However, we considered it meaningful to present the end result visualization as a proof of concept.

Figure 8 (a) shows the experimental test site located in Otaranta, Espoo, Finland. The test site was 150 m long and 6 m wide. The adjacent areas to the road section were parking areas and lawns. The section consisted of five luminaires. The 100 W high pressure sodium luminaires were being mounted at the height of 10 m. Figure 8 (b) illustrates the stationary luminance measurement registered with a 3D point cloud scanned with the Faro Focus 3D terrestrial laser. The luminance measurement was performed with the Nikon D800E with aperture f/5.6, exposure time 8 s, and ISO 100. The laser scanner used was a Faro Focus 3D continuous-wave infrared laser scanner with a 305°×360° field of view. The luminance image and the laser scanning data were combined manually. The orientation of undistorted images was resolved relative to the individual laser scans’ intensity images. In the registration, the mean distance between the selected points in the RGB image and the 2D projection of the 3D points was 4.7 pixels for each image pair. The lower resolution of the TLS intensity images was the main reason for the registration uncertainty. A detailed description of the site and the data fusion is presented in a study by Vaaja et al. (2015).

Combining luminance images with mobile laser scans was tested at Munkkiniemenranta, Helsinki, where the experiments were carried out in night illumination on a stretch of two-lane road 800 meters in length. The street section was covered by trees that cast shadows on the road surface. The
luminaires at Munkkiniemenranta were 8450 lumen AEC Illuminazione LED luminaires mounted at a height of 8 meters. The spacing between two adjacent luminaires was 33 meters. A mobile-measured luminance point cloud was created utilizing a Trimble MX2 (Trimble, 2017). In the Trimble MX2, imaging was executed with a Ladybug3 panoramic camera. The stretch of road was mapped in both directions and material was collected over a period of about 10 minutes. Equipment preparation and the initialization of the location system, taking into account the measurement site, took about 30 minutes. The laser scanning material of the site consists of 40 million point observations. The panorama camera was set up to take images at two-second intervals. The exposure time used was 50 ms, and gain was set to 18 dB.

Figure 8. (a) The study area for TLS measurements; (b) A snapshot from a 3D point cloud into which luminance values have been mapped. Red indicates the highest luminance, which intuitively resides directly below the street luminaires.

In the post-processing of the material, the mapping system’s location data and the measurement route were calculated using Applanix POSPac MMS software to create a virtual reference station (VRS) base station network around the measurement area. The measurements produced by the laser scanning were combined with the location data in the Trimble Trident software, where the measurement observations were also combined with the RGB values from the images taken with the panorama camera. Luminance calibration of the panorama camera enabled a final luminance value (cd/m²) to be calculated for every measurement point. Figure 9 illustrates the luminance data registered to the mobile-scanned 3D point cloud.

Figure 9. Luminance data integrated into mobile laser-scanned point cloud. The colorbar indicates the luminance values in cd/m².
4. DISCUSSION

In this study, we presented the preparation for a digital camera in order to use it as an imaging luminance photometer combined with a mobile or terrestrial laser scanning system. The target area of use for this system was a night-time road environment. We achieved initial luminance data and 3D point cloud integration for TLS as well as MLS systems.

In order to be applicable to road lighting measurements, the measurement system should perform for luminances of at least 0.10–3.0 cd/m$^2$. This luminance range is defined for the variety of road classes in the international standard for road lighting, CEN/TR 13201:2015 (CEN/TR, 2015).

In stationary luminance measurements, the target luminance range was achieved. Using the Nikon D800E at ISO 100 and aperture f/5.6, the usable luminance range of a single measurement was 0.01–2.88 cd/m$^2$. Moreover, by combining several measurements, the luminance range can be extended.

For mobile measurements, the target luminance range was compromised. Using the Nikon D800E (ISO 3200, f/2.8), the usable luminance range was 0.44–27.97 cd/m$^2$; and using the Ladybug3 (50 ms, 18 dB), it was 0.99–8.63 cd/m$^2$. The mobile measurement luminance range is limited because a long exposure time cannot be used. A short exposure time is compensated for by increasing the sensor sensitivity, which reduces the signal-to-noise ratio. Especially for low luminance values, noise increases the relative measurement uncertainty to an unusable level. In mobile measurements, the luminance range can be extended towards the low end only by reducing the movement velocity, or by accepting more motion blur in the measurements. With a mobile measurement velocity of 10 m/s and a shutter speed of 1/125 s, the luminance information is averaged over 0.08 m in the direction of the movement. If we compromise on a slower measurement speed of 5 m/s and a more severe motion blur of 0.16 m, we can measure luminances as low as 0.11 cd/m$^2$ using the Nikon D800E and 0.25 cd/m$^2$ with the Ladybug3.

The tradeoff between existing panoramic imaging systems and single lens reflex cameras in luminance measuring from moving platforms is apparent: the panoramic camera systems are geometrically pre-calibrated and significantly simpler to integrate into an MLS system. If 360-degree panoramic images are required, the use of a DSLR is further complicated. However, due to the low performance of panoramic cameras in low-light conditions, their luminance-measuring accuracy and dynamic range is lower than that of DSLR cameras. The choice of imaging system is also affected by the velocity of the platform used. At higher speeds, the acquisition frequency of DSLR cameras becomes a limitation.

Four aspects of luminance measurements were not considered in this study: flicker, glare, spectral power distribution, and mesopic photometry. Flicker is the temporal modulation of a light source’s light intensity. It is often present in electrically powered light sources. The type of flicker depends on the light source and varies in terms of modulation depth and modulation frequency (Bodington et al., 2016). Flicker causes measurement uncertainty in luminance measurements, as the lighting output varies over time. The measurement uncertainty can be severe when the modulation depth is prominent and the measurement time is close to or shorter than the duration of the modulation cycle.

One regulated road lighting measure is the threshold increment, TI. It quantifies the disability glare caused by the road luminaires. In this study, we concentrated on the low-level luminances (0.10–3.0 cd/m$^2$) of the road surface. In order to be applicable to glare measurements, the luminance
photometer should also be able to measure luminances as high as 100,000 cd/m². In stationary measurements, the solution to glare measurement is high dynamic range photography. Similarly, in mobile measurements, HDR photography can be applied with multiple cameras or multi-camera systems, but it will need more attention to synchronization and exposure settings.

In luminance measurement, the spectral power distribution (SPD) of the light source should be considered. As the luminance is recorded in RGB values, the actual spectrum is simplified. High color saturation of a measured surface increases the measurement error (Anaokar and Moeck, 2005). Furthermore, the measured luminance also depends on the SPD of the light source (İnanici, 2006). SPDs with prominent peaks and valleys (such as the SPD of high pressure sodium) may decrease the measurement accuracy. In order to increase the luminance measurement accuracy, the spectral behavior of the imaging luminance photometer should be characterized.

Mesopic photometry is strictly related to the spectral power distribution of light. The luminances on the road surface are often in the mesopic luminance region: 0.005–5.0 cd/m². To improve accuracy in this luminance range, a system for mesopic photometry should be implemented (CIE, 2010). To implement the system, the state of the observer’s adaptation and the ratio between the scotopic and the photopic SPDs (S/P ratio) of the light source must be known. Presently, the determination of the observer’s state of adaptation is not completely defined. In this article, only photopic luminances were considered.

Certain aspects causing uncertainty in calibration, and the combined uncertainty of the whole system were not considered. One possible cause for uncertainty in the luminance calibration is temperature. Temperature changes may affect both the noise in the sensor, and by thermal expansion, the physical dimensions in the camera.

One of the future objectives is to register the captured luminance data into the 3D points with high fidelity and pace. This would demand a fluent workflow and an increased level of automation in the data management. Hence, the luminance mapping of roads could be performed in parallel to MLS road inventories. MLS point clouds have been used for feature extraction. The luminance mapping can even be part of the future tandem mobile-UAV collaborative system (Molina et al., 2017). Tandem mobile-UAV collaborative systems are not limited to the eye-of-sight problems related to UAVs, and thus these systems are extremely feasible for corridor mapping applications. In such systems, the road environment is mapped from both the road and the air in order to have thorough understanding of the road environment without shadows in the data. Additionally, future autonomous vehicles will include both the MLS and cameras onboard, allowing the use of the data for advanced interpretation tasks—even for the luminance mapping. There are plenty of innovative future concepts where luminance mapping can be integrated if the processing technology has been fully developed. Furthermore, built environment planners and designers could utilize the road inventories enhanced with the night-time luminance data (Tetri at al., 2017). Thus, this would improve the interaction between architects, city planners, and lighting designers.

5. ACKNOWLEDGMENTS

This research project was supported by the Academy of Finland, the Centre of Excellence in Laser Scanning Research (CoE-LaSR) (No. 272195, 307362), “Competence-Based Growth Through Integrated Disruptive Technologies of 3D Digitalization, Robotics, Geospatial Information and Image Processing/Computing–Point Cloud Ecosystem”, pointcloud.fi (No. 293389), the Aalto Energy Efficiency Research Programme (Light Energy—Efficient and Safe Traffic Environments
project), the EUE project (2141226), the European Regional Development Fund "Leverage from the EU 2014–2020” projects "Soludus" (301192) and “AKAI” (301130), the Finnish Funding Agency for Innovation project “VARPU” (7031/31/2016), and the Aalto University Doctoral programme.

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