

Article

# Building lighting device inventories with the LANcube v2 open source multiangular radiometer

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**Abstract:** This paper describes the use of an open source instrument called LANcube v2 to build a lighting device inventory. The LANcube v2 is an instrument having 5 color sensitive sensors, each on a face of a cube. The instrument can be mounted on a car roof in order to create a map of the artificial light at night while roaming the streets and roads. Based on the temporal variations of the detected signal on various cube's faces, we developed a method of finding the position in 3D of each lighting device. The lamp spectral types can be determined thanks to the color balance of the raw Red (R) Green (G) Blue (B) and Clear (C) color bands. If one assumes a typical angular photometry of a lighting device with respect to its location, it is possible to estimate its luminous flux. Such information allows us to build a lighting devices inventory of a territory. One advantage of that new method is that it can provide information about the private lighting devices that are always excluded from public lighting inventories. We will compare the inventory extracted with that new methodology with an in situ lamp inventory made for two villages in Canada. This will allow us to emphasize the strengths and limitations of the method by comparing to the ground truth.

**Keywords:** Remote sensing; Night; Light pollution; streetlight; radiometer; Lighting device inventory

## 1. Introduction

In the recent years, obtrusive light has been found to affect the entire environmental equilibrium. The Artificial Light at Night (ALAN) can perturb health of many species (animals, insects and plants) including humans [1–7]. ALAN can be divided into two main components the direct and indirect ALAN. Indirect ALAN is the component reaching the environment after scattering in the atmosphere. This component is often referred as artificial sky brightness. On the other hand, direct ALAN does not interact significantly with the atmosphere and therefore reach almost directly the environment. This component is often referred as obtrusive light. The latter component is many orders of magnitude higher than the indirect component for urban environments or for sites located within a few tenths of meters to a lighting device.

In order to study the effect of ALAN, it is required to monitor it through color sensitive measuring devices. The spectral content or color of the ALAN is important because that many biological processes involved in the ALAN induced perturbations are wavelength dependant. But not only the spectrum matters, the orientation of the light propagation too. Ideally, the measuring devices must be multispectral and multiangular. In the present work, we describe the use of such a sensor called LANcube [8].

To get even more detailed information on the effect of the ALAN, one promising approach is to use radiative transfer models. But modeling of the obtrusive light during the night requires the knowledge of many environmental parameters. Among the most important to know are the lighting device positions, spectral types, luminous fluxes and angular emission functions. In this paper, we show how the analysis of the data recorded by the LANcube may deliver at least an estimation of

most of these variables. To achieve that, the LANcube needs to be installed on top of a vehicle roaming streets and roads. In our methodology, we assume that the angular emission function of the lighting device is isotropic. That is of course a major weakness of the method which in general implies an overestimation of the lamp height and of the distance to the source. The examination of many street light photometric Illuminating Engineering Society (IES) files showed us that the approximation is better for High Intensity Discharge (HID) technology than for the LED technology. The typical span of increase of the emission functions toward larger nadir angles for LED streetlights, result in larger overestimates of the height and lateral distance.

## 2. The LANcube v2 device

The LANcube is a device designed to sample the multispectral and multiangular properties of the direct ALAN. The LANcube is a cube-shaped system having a 4 color band sensor on five of its faces. The latest version (v2) of the LANcube has shorter acquisition time than the original version. In the darkest conditions, it can read the 5 sensors every 0.6 seconds. This acquisition rate allows to monitor the temporal change in light irradiance reaching the sensor while in movement. Given that the LANcube v2 also comprise a Global Positioning System (GPS), its position can be recorded at each sensor reading. The temporal and positional information can be combined to infer the properties of the lighting devices encountered along the path.

The LANcube is equipped with a WIFI interface which allows an access to the data from a mobile device. The LANcube is developed in an open science approach so that the recipe to build the LANcube along with its software is released under open licenses [9]. For a better power stability, the LANcube has an integrated Uninterruptible Power Supply (UPS). The picture of LANcube v2 is shown in Figure 1.



**Figure 1.** The LANcube v2 radiometer. On the bottom of the left face, are the USB and ethernet ports and on the right face one can see the operating switch and status RGB LED. At the center of each face lies a light color sensor. The size of the LANcube v2 is 9x9x9 cm.

### 3. Analysing the signal recorded by the LANcube

Thanks to its high sampling frequency, it is now possible to extract spatial information about the lighting devices out of the temporal variations of the LANcube v2 sensor's signals. To do so, the LANcube v2 needs to be moved. This is usually done while the LANcube v2 is installed on top of a vehicle roaming along the roads and streets. In this section we will derive the equations allowing to determine the position, height, spectral type and luminous flux of the lighting devices located along or nearby a street or a road.

In this method, we exploit the two lateral sensors along with the top sensor. As for the LANcube v2 sensor numbering, the sensor on the side that is on the right when one is looking forward is sensor #3, the opposite face holds sensor #5 while the top face holds sensor #1.

The idea behind the detection of the lighting devices rely on the temporal analysis of sensors illuminance along the LANcube trajectory. The problem splits into five cases because that the lighting device may be directly above, completely on the right handed or left handed side or above in an oblique direction on each side.

#### 3.1. Lighting devices spectral type recognition

To determine the spectral type, we make use of the color ratios relatives to the green channel in order to determine the coordinate of the lighting device in a 3D color space defined by the red/green, blue/green and infrared/green color ratios ( $r/g$ ,  $b/g$  and  $i/g$ ).  $r$ ,  $g$ ,  $b$  and  $i$  are derived from the raw red, green, blue and clear ( $R,G,B,C$ ) LANcube channels as explained in [8]. Basically, we first use the sum of the 3 colors and the clear channel to get an estimate of the near infrared ( $i$ ). Then we correct the raw colors ( $R,G,B$ ) channels by subtracting the infrared estimate to get the infrared-free colors ( $r,g,b$ ).

We recorded the light with the LANcube v2 for many reference lamps of different typical lamp spectral types. We actually sampled High Pressure Sodium (HPS), Metal Halides (MH), Mercury Vapor (MV), Light-Emitting Diodes (LED) at different Correlated Color Temperature (CCT), and Incandescent (INC). This allows to map in the 3D color space different positions for a variety of the targeted technologies (or spectral types). That database is given in Table 1. The content of the table will evolve in the future as long as new lamps will be identified and sampled.

The spectral type of a given lighting device detected by the LANcube v2, is identified by finding the smallest distance ( $\delta_{min}(s)$ ) out of the distances relative to each lamp ( $\delta(s)$ ) type of Table 1 in the 3D color space defined by the color ratios  $r/g$ ,  $b/g$ , and  $i/g$ . Note that the  $r/g$  ratios are multiplied by a factor of 0.14 to better discriminate the different technologies because that the span of values for that ratio is larger than the two others (without considering the incandescent that has a very high  $i/g$  ratio). For some LED spectra, the  $i/g$  ratio can be negative. It simply reflects the complex combination of the spectra and the bands spectral sensitivities. In other words  $i$  is not really a pure infrared signal, but is still useful to better discriminate spectral types.

$$\delta(s)^2 = 0.14^2 ([r/g] - [r/g]_s)^2 + ([b/g] - [b/g]_s)^2 + ([i/g] - [i/g]_s)^2 \quad (1)$$

#### 3.2. Lighting devices position

When looking at the temporal signal of sensors #1, #3 and #5, one should note that at some moments the signals reach a local maximum and then decline until another maximum is observed. The maximum signal indicates that the LANcube v2 is located aside and or below a lighting device. If we detect only a maximum on sensor #1 that means that the lighting device is located directly above the LANcube. On the other hand, if the maximum is only on the #3 or #5, the lighting device is located on the side at about the same height or below the LANcube height. A peak on sensor #3 means a lighting device on the right side of the car while on sensor #5 it is located on the left side. If the maximum on sensor #1 coincide with a maximum on sensors #3 or #5, the lamp is higher to the LANcube on the side.

**Table 1.** Coordinates of the various typical lamp spectrum in the 3D color space.

$[r/g]_s$	$[b/g]_s$	$[i/g]_s$	$u$	Spectral type
2.64	0.60	0.07	0.03	HPS
2.50	0.65	0.07	0.03	HPS
2.79	0.59	0.16	0.03	HPS
3.47	0.74	0.25	0.03	HPS
2.50	0.77	0.11	0.03	HPS
2.27	0.84	0.50	0.03	HPS
2.21	0.67	0.07	0.03	HPS
2.84	0.71	0.16	0.03	HPS
0.87	0.98	0.22	0.05	MH4000
0.80	0.54	0.15	0.10	MV
1.01	0.57	0.36	0.10	MV
5.43	0.64	0.17	0.00	LED1500
1.94	0.42	-0.11	0.00	LED1650
1.64	0.38	-0.08	0.00	LED1650
3.87	0.47	0.13	0.00	LED1800
2.65	0.43	-0.10	0.00	LED1800
2.37	0.44	-0.15	0.00	LED1800
3.42	0.51	0.03	0.00	LED1800
2.91	0.49	0.01	0.00	LED1800
1.85	0.56	0.03	0.00	LED2200
1.99	0.75	0.04	0.00	LED3000
1.87	0.69	0.02	0.00	LED3000
0.81	0.51	-0.11	0.00	LED3500
1.04	0.77	-0.03	0.00	LED4000
1.00	0.67	-0.06	0.00	LED4000
0.95	0.58	-0.09	0.00	LED4000
1.21	0.89	0.02	0.00	LED5000
0.99	0.84	0.02	0.00	LED5500
0.60	0.81	-0.09	0.00	LED5500
3.38	0.83	3.65	0.30	INC2550
2.79	0.82	2.37	1.30	INC2550

### 3.2.1. Removing the background light

Given that we are only interested in the detection of the direct light coming from a lighting device, we need to remove the light reaching a sensor after a reflection on nearby surfaces (facades or ground). This is done independently for each sensor. To do so we are using a 7 data sliding window, keeping the minimum value. The minimum value is simply removed from the original signal. We therefore obtain the cleaned illuminance for sensors #1, #3 and #5, respectively denoted  $E_{v1}(t)$ ,  $E_{v3}(t)$  and  $E_{v5}(t)$ .

### 3.2.2. Case 1: lighting device higher than the LANcube on the side

To simplify the discussion, we will focus on sensors #1, #3 which are related to a detection above or on the right side. But the same analysis may be done with the left side simply by replacing sensor #3 by sensor #5.

When maximums on  $E_{v1}$  and  $E_{v3}$  coincide, it means that we are aside a lighting device higher than the LANcube. In that case, we have enough data to determine the lighting device position relative to the LANcube position.

Figure 3 illustrates the geometry of a typical street with a lighting device higher than the LANcube and on the side. In that figure,  $h$  is the height of the LANcube relative to the street,  $H$  the height of the lighting device,  $d$  is the horizontal distance between the lighting device and the LANcube, and  $\theta$  is the nadir angle of the line from the lighting device to the LANcube.

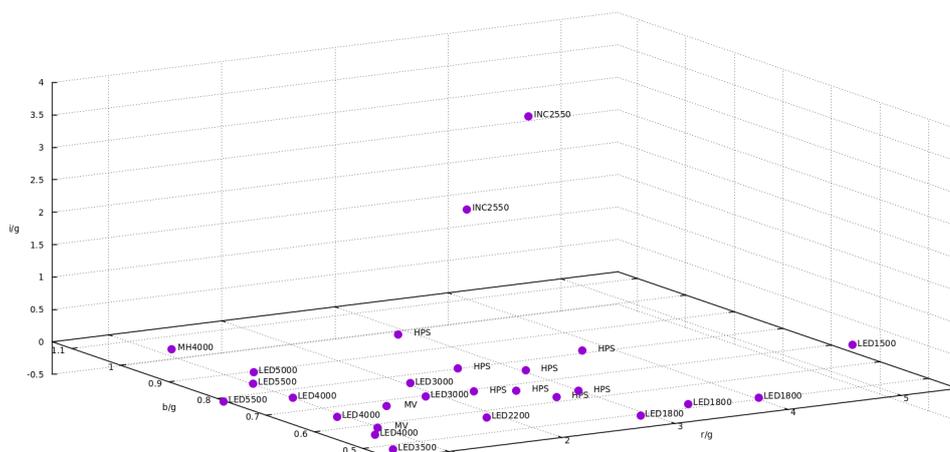


Figure 2. Lamp spectra in the color space.

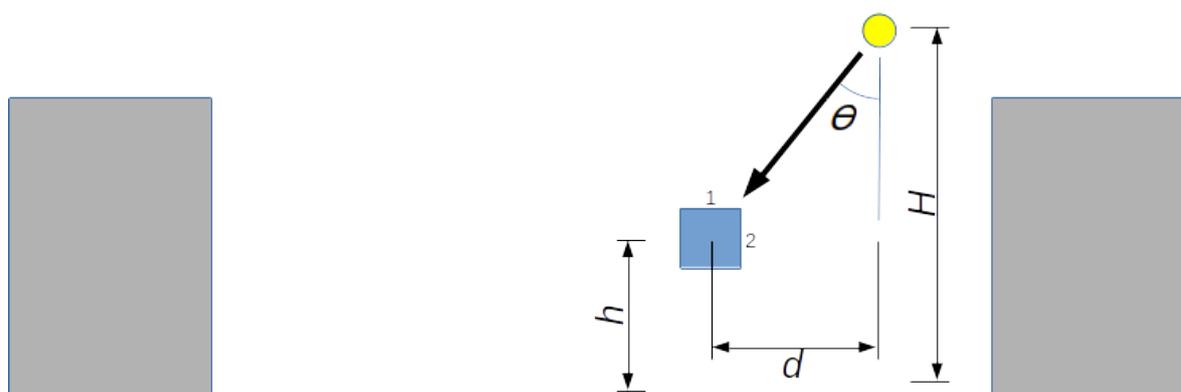


Figure 3. Geometry of a street.

Since that the sensor angular sensitivities are very close to a cosine function, we can express the local maximum signals as a function of the signal normal to the direction of the lighting device  $E_{v\perp}$ . This gives Equation 2 for the upper sensor, and 3 for the side sensors.

$$E_{v1} = E_{v\perp} \cos(\theta) \quad (2)$$

$$E_{v3} = E_{v\perp} \cos(\pi - \theta) = E_{v\perp} \sin(\theta) \quad (3)$$

Simple geometry allows to formulate the following relationship.

$$\tan(\theta) = \frac{d}{H - h} \quad (4)$$

With the definition of a tangent along with Equations 2 and 3 we can write:

$$\tan(\theta) \equiv \frac{\sin(\theta)}{\cos(\theta)} = \frac{E_{v3}}{E_{v1}} \quad (5)$$

We assume that  $h$  is known. After combining Equations 4 and 5, we obtain:

$$H - h = d \frac{E_{v1}}{E_{v3}} \quad (6)$$

From figure 4, we can write the following expression assuming that the LANcube moved of a distance  $D$  along the street. If we also assume that between the two positions, the change in the angular emission function of the lamp is negligible we can write the two following Equations.

$$E_{v1} \approx \frac{I \cos(\theta)}{(H - h)^2 + d^2} \quad (7)$$

$$E'_{v1} \approx \frac{I \cos(\theta')}{(H - h)^2 + d^2 + D^2} \quad (8)$$

Where  $I$  is a constant and  $E'_{v1}$  is the illuminance falling on sensor #1 at  $t'$ . To be valid one should use a relatively small value of  $D$  compared to the lighting device distance or a lighting device having a very low change in its emission function along the street direction. We actually assume that the emission function is constant.

Taking the ratio of Equation 7 over 8 we get:

$$\frac{E_{v1}}{E'_{v1}} = \frac{\cos(\theta) ((H - h)^2 + d^2 + D^2)}{\cos(\theta') ((H - h)^2 + d^2)} \quad (9)$$

We can write the two cosines as follow.

$$\cos(\theta) = \frac{H - h}{\sqrt{(H - h)^2 + d^2}} \quad (10)$$

$$\cos(\theta') = \frac{H - h}{\sqrt{(H - h)^2 + d^2 + D^2}} \quad (11)$$

By combining Equations 9, 10 and 11, we can write the following Equation.

$$\frac{E_{v1}}{E'_{v1}} = \left( \frac{(H - h)^2 + d^2 + D^2}{(H - h)^2 + d^2} \right)^{3/2} \quad (12)$$

If we replace  $(H - h)$  in Equation 12 with Equation 6 we can write the following equation.

$$\frac{E_{v1}}{E'_{v1}} = \left( \frac{\left( \frac{dE_{v1}}{E_{v3}} \right)^2 + d^2 + D^2}{\left( \frac{dE_{v1}}{E_{v3}} \right)^2 + d^2} \right)^{3/2} \quad (13)$$

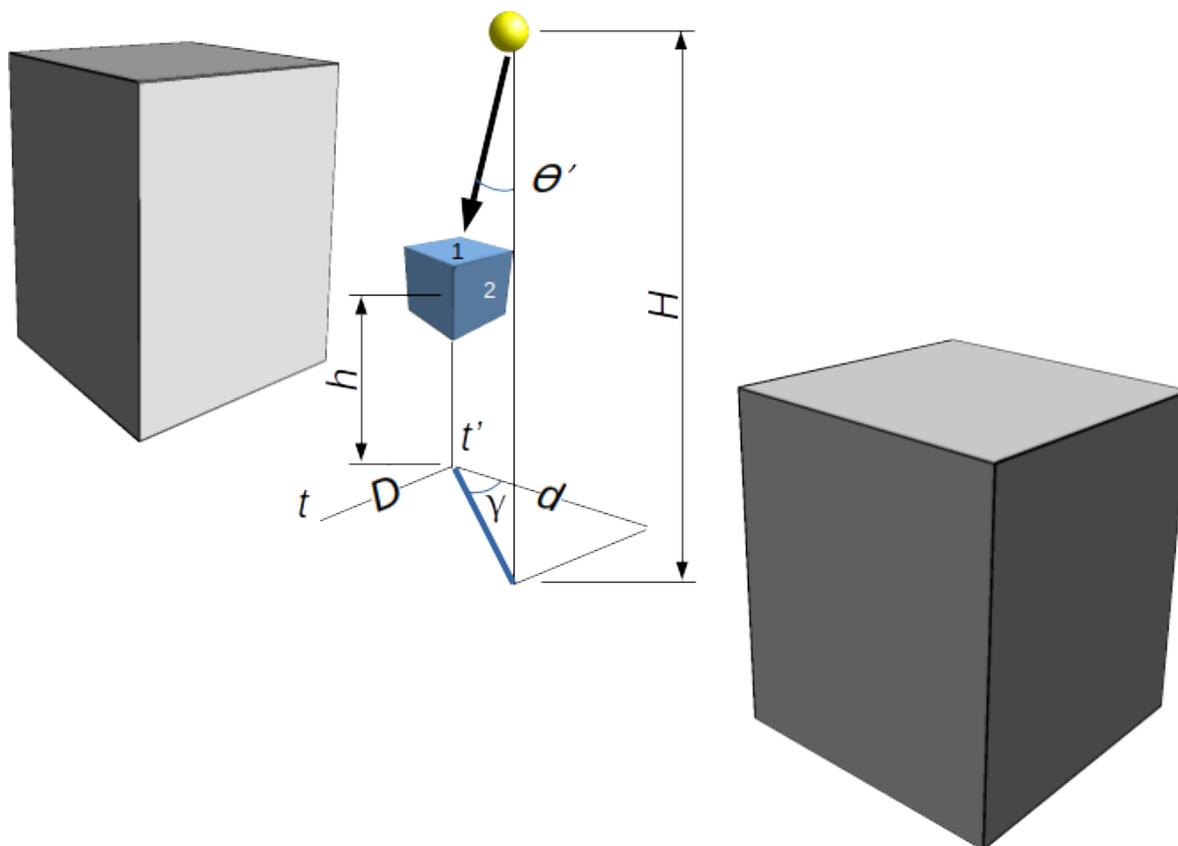
After some manipulations, we can find an expression for  $d$  which is the horizontal distance between the LANcube and the lighting device normal to the street at  $t$ .

$$d = \frac{D}{\sqrt{\left( \frac{E_{v1}}{E'_{v1}} \right)^{2/3} \left( \left( \frac{E_{v1}}{E_{v3}} \right)^2 + 1 \right) - \left( \frac{E_{v1}}{E_{v3}} \right)^2 - 1}} \quad (14)$$

We will see in a later section how  $D$  can be determined out of the latitude-longitude coordinates of the two corresponding LANcube positions.

Knowing the value of  $d$  we can now determine the height of the lighting device relative to the ground ( $H$ ) by using Equation 6.

$$H = d \frac{E_{v1}}{E_{v3}} + h \quad (15)$$



**Figure 4.** The geometry of an acquisition after the local maximum when the LANcube moved by a distance  $D$  along the street.

With Equations 2 and 10, we can determine the illuminance normal to the line between the LANcube and the lighting device.

$$E_{v\perp} = \frac{E_{v1}}{\cos(\theta)} = \frac{E_{v1}\sqrt{(H-h)^2 + d^2}}{H-h} \quad (16)$$

### 3.2.3. Case 2: Lighting device directly above the LANcube

This situation happens when only a maximum is detected on sensor #1. Assuming that the LANcube moved of a distance  $D$  along the street in time  $t'$  and that between the two positions, the change in the angular emission function of the lamp is negligible we can write the two following equations.

$$E_{v1} \approx \frac{I}{(H-h)^2} \quad (17)$$

$$E'_{v1} \approx \frac{I \cos(\phi')}{(H-h)^2 + D^2} \quad (18)$$

Similarly to Equation 11,  $\cos(\phi')$  can be expressed as follows.

$$\cos(\phi') = \frac{H-h}{\sqrt{(H-h)^2 + D^2}} \quad (19)$$

Combining Equations 17, 18 and 19 we obtain the following relationship between  $E'_{v1}$  and  $E_{v1}$ .

$$\frac{E'_{v1}}{E_{v1}} = \left( \frac{(H-h)^3}{((H-h)^2 + D^2)^{3/2}} \right) \quad (20)$$

After some manipulations we obtain.

$$H = \frac{D \left( \frac{E'_{v1}}{E_{v1}} \right)^{1/3}}{\sqrt{1 - \left( \frac{E'_{v1}}{E_{v1}} \right)^{2/3}}} + h \quad (21)$$

In that case  $d = 0$ .

We can easily determine the illuminance normal to the line between the LANcube and the lighting device.

$$E_{v\perp} = E_{v1} \quad (22)$$

### 3.2.4. Case 3: lighting device at LANcube height on the side

We can assume that a lighting device is located at or below the LANcube height  $h$  on the side when a maximum is only detected on  $|E_{v3}|$ . In such a case we assume that the lighting device is at the LANcube height. Assuming again that the LANcube moved of a distance  $D$  along the street in time  $t'$  and that between the two positions, the change in the angular emission function of the lamp is negligible we can write the two following equations.

$$E_{v3} \approx \frac{I}{(d)^2} \quad (23)$$

$$E'_{v3} \approx \frac{I \cos(\phi'')}{d^2 + D^2} \quad (24)$$

Similarly to Equation 11,  $\cos(\phi'')$  can be expressed as follows.

$$\cos(\phi'') = \frac{d}{\sqrt{d^2 + D^2}} \quad (25)$$

Combining Equations 23, 24 and 25 we obtain the following relationship between  $E'_{v3}$  and  $E_{v3}$ .

$$\frac{E'_{v3}}{E_{v3}} = \frac{d^3}{(d^2 + D^2)^{3/2}} \quad (26)$$

After some manipulations we obtain.

$$d = \frac{D \left( \frac{E'_{v3}}{E_{v3}} \right)^{1/3}}{\sqrt{1 - \left( \frac{E'_{v3}}{E_{v3}} \right)^{2/3}}} \quad (27)$$

In that case we assume  $H = h$ .

We can determine the illuminance perpendicular to the line between the LANcube and the lighting device.

$$E_{v\perp} = E_{v3} \quad (28)$$

### 3.3. Estimating the luminous flux

We get a rough estimate of the luminous flux of the lighting device ( $\Phi_v$ ) assuming an upward light output ratio ( $u$ ) and a conversion constant  $K$ .

$$\Phi_v \approx \frac{2\pi K E_{v\perp} (d^2 + (H-h)^2)}{(1-u)} \quad (29)$$

The value  $u$  is determined per spectral types as indicated in Table 1. These numbers can be modified by the user according to the typical local properties of the lighting devices.

The  $K$  constant can be estimated after using many in situ measurements for lighting device with known flux. This constant is directly related to the photometric type of the lighting device and to the detection point relative to the lighting device position. Our goal here is not to determine accurately the luminous flux, but rather to estimate it roughly. We verified, with IESNA files of some usual type III street lights, that  $K = 1$  is a reasonably good choice.

### 3.4. Converting distance to latitude and longitude and vice versa

The LANcube v2 record the latitude ( $\phi$ ) and the longitude ( $\lambda$ ) at every acquisition. For that reason, we must be able to convert the distance to the lighting device in term of its latitude and longitude. To accomplish that, we need to convert  $(\phi, \lambda)$  of the local maximum into  $(x, y)$  in meter and then determine  $(x_l, y_l)$  the position of the lighting device in that reference system. Then, once defined we can go back to the  $(\phi_l, \lambda_l)$  position in the latitude-longitude system.

A change in  $x$  or  $y$  coordinates can be defined respectively as  $\Delta x$  and  $\Delta y$ .

$$\Delta y = y' - y \approx \frac{\pi}{180} R \Delta\phi \quad (30)$$

$$\Delta x = x' - x \approx \frac{\pi}{180} R \Delta\lambda \cos(\phi) \quad (31)$$

Where  $\Delta\phi = \phi' - \phi$  and  $\Delta\lambda = \lambda' - \lambda$  are respectively variations in latitude and longitude. In Equations 30 and 31,  $R$  is the radius of the earth (6 373 000 m).

In the special case where  $\Delta x$  and  $\Delta y$  are the displacement between the positions of the LANcube at  $t$  and  $t'$ , the distance along the path of the LANcube  $D$  is given by Equation 32.

$$D = \sqrt{\Delta x^2 + \Delta y^2} \quad (32)$$

One can combine Equation 32 with Equations 30 and 31 to determine  $D$  as a function of the variations in latitude and longitude between times  $t$  and  $t'$ .

The unit vector components defining the displacement of the LANcube v2 between  $t$  and  $t'$  can be determined with Equations 31 and 30.

$$\hat{X} = \frac{(\lambda' - \lambda)\cos(\phi)}{\sqrt{((\lambda' - \lambda)\cos(\phi))^2 + (\phi' - \phi)^2}} \quad (33)$$

$$\hat{Y} = \frac{(\phi' - \phi)}{\sqrt{((\lambda' - \lambda)\cos(\phi))^2 + (\phi' - \phi)^2}} \quad (34)$$

This unit vector can be converted into the unit vector toward the lighting device from position at  $t$  simply by rotating of  $\epsilon = -\pi/2$  for a lighting device located to on the right side or  $\epsilon = \pi/2$  on the left side.

$$\hat{x} = \hat{X}\cos(\epsilon) - \hat{Y}\sin(\epsilon) = -\hat{Y}\sin(\epsilon) \quad (35)$$

$$\hat{y} = \hat{X}\sin(\epsilon) + \hat{Y}\cos(\epsilon) = \hat{X}\sin(\epsilon) \quad (36)$$

Considering that the lighting device is at a distance  $d$  from the point of maximum illuminance  $(x, y)$ , we can express the position of the lighting device  $x_l$  and  $y_l$ .

$$x_l = d \hat{x} + x \quad (37)$$

$$y_l = d \hat{y} + y \quad (38)$$

This displacement can be converted back to changes in latitude and longitude with Equations 31 and 30 and then find the geographical co-ordinates of the lighting device  $(\phi_l, \lambda_l)$ .

$$\lambda_l = \frac{180(x_l - x)}{\pi R \cos(\phi)} + \lambda = \frac{180\hat{x}d}{\pi R \cos(\phi)} + \lambda \quad (39)$$

$$\phi_l = \frac{180(y_l - y)}{\pi R} + \phi \quad (40)$$

### 3.5. Improving the data with local statistics

We assume that the emission function does not change significantly between  $t$  and  $t'$ . Such assumption can result in errors in lighting device position and height, which reflected in the evaluation of the luminous flux. Another factor that can introduce errors is the blocking of the light by canopy or other smooth obstacles. Generally the error translates in incredibly high luminous fluxes along with large lamp heights. One manner to correct for these errors is to analyze height distribution of nearby lighting devices. Then we assume that the incorrect lamp is likely to be at the most common height of nearby lamps that are significantly higher than the LANcube (we set a threshold at 4 m to exclude the car headlights and residential lights). Then we change the erroneously detected height to the most common nearby value. The corresponding positions and luminous flux may be re-scaled to that new assigned height ( $H'$ ). If we define the initially determined height, distance and luminous flux as  $H$ ,  $d$  and  $\Phi_v$ , the new values ( $d'$  and  $\Phi'_v$ ) are computed with Equations 41 and 42.

$$d' = d \frac{H' - h}{H - h} \quad (41)$$

$$\Phi'_v = \Phi_v \left( \frac{H' - h}{H - h} \right)^2 \quad (42)$$

## 4. Results and discussion

After applying the method described above, we obtain a lighting device inventory for the places where we roam with the LANcube on top of a car. When examining that inventory we noticed a number of sources having flux lower than 250 lumens, which is not expected since typical residential light bulbs have about 400 to 500 lumens. After a closer analysis, we found that these very low sources often correspond to road panel signs. So they are the light of a nearby streetlight reflected in the panel. For that reason, we are removing all sources having a luminous flux lower than 250 lumens. Figures 5, 6 and 7 show the results for two villages located in the province of Québec, Canada. The inventory extracted contains the latitude and longitude, height relative to the ground, luminous flux and the spectral type. At a first glance we can notice that the different municipal administration delivers very different lighting practices. In Saint-Camille, most lighting devices are HPS with relatively low luminous flux, most of them being below 4000 lumens. On the opposite, in Stoke we see that the dominant technology are LED at 4000K and most flux is higher than 6000 lumens. It is noticeable that Stoke replaced their HPS lamps for 4000K LED some years ago and when looking to the few remaining HPS, the new flux is generally more than ten times the HPS ones.

To evaluate the validity of the method, it is important to compare the extracted inventory with the ground truth. We performed that comparison on the height and the spectral type extracted. We excluded the luminous flux from that comparison simply because we do not know that information



Figure 5. Detected spectral types and luminous fluxes in Saint-Camille, Québec, Canada.



Figure 6. Detected spectral types and luminous fluxes in central part of Saint-Camille, Québec, Canada.

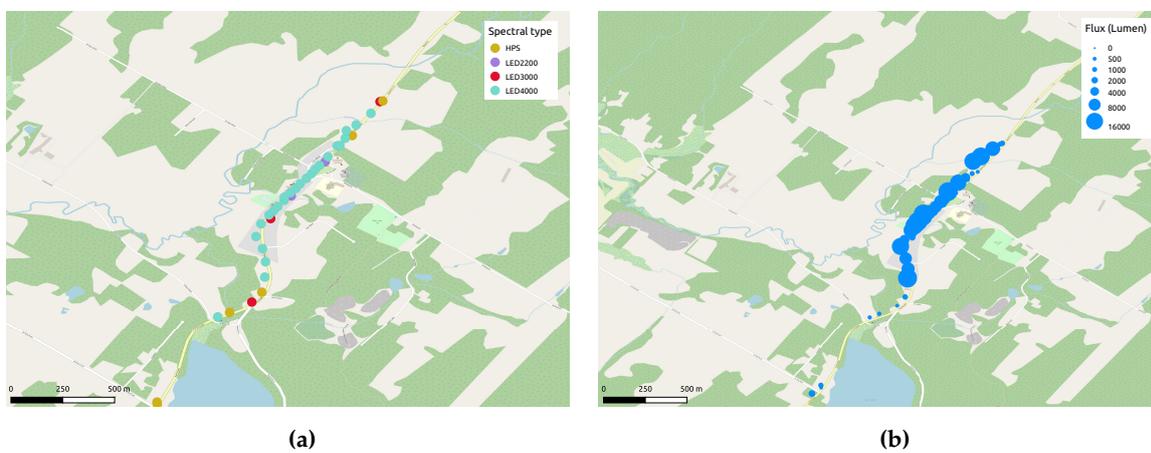


Figure 7

from the ground truth inventory. We also compared the detection success defined as the number of detected sources within a buffer distance of 17 meters from the position of the devices included in the ground truth inventory. In this latter comparison, we do not care if the method determined correctly the technology and height, we only focus on the position. The buffer distance was determined on the basis of the typical detection distance away from the LANcube position. 17 m may appear large, but the GPS accuracy during the sampling is of the order of 8 meters and at 50 km/h, we only have a measurement point every 9 meters. Combination of the two uncertainty gives  $\approx 18\text{m}$  which is coherent with 17 m buffer used. To confirm the significance of that buffer distance, we compared the position of the same set of lighting devices as detected during two consecutive detection experiments. This gives an average error of 12 meters with a dispersion around that value having a standard deviation of 7 meters, i.e. 19 m. This is similar to the buffer distance. To exclude multiple detection of the same source, we merged the detected lighting systems of the same spectral type. The merge is only performed when the lighting devices are detected at least 20 seconds of interval from each other (i.e. two different paths). In such case, the position, height and luminous flux of the merged device is set as the average of the original values. The maximum distance for the merging of two sources was set to 25 m which is in our case the minimum distance between two similar street lights in the villages. This value can be changed for other territories as it is a parameter of the script input file. In our case we tried different values to find that one to give the best results. In any case according to our localization accuracy at 50 km/h, this number should not be lower than 17 m or 13 m at 25 km/h. The average distance between street lights in the village center is  $\sim 60\text{ m}$  while it lies between 120 m and 1 km out of the village center. One major advantage of the merging process is that one can perform many consecutive scans of a road to increase the accuracy of the inventory.

In Saint-Camille and Stoke, no lighting systems were detected farther than 25 m off the road. Most of the lighting systems were detected within 15 m from the road.

In addition to street lights and some private parking lights, 48 private lights were detected in the two villages. Most of them are small residential bulbs installed on house and building facades typically at lower heights compared to street lights (less than 4 m). We excluded the lower heights private lights from the ground truth comparison because it was almost impossible to validate where they are located and if they were on or off during the sampling experiment.

Table 2 shows the results of the comparison between the values detected by the LANcube and the ground truth. Only one source out of 74 was not detected by the LANcube (3%). It is located in a zone where the car speed was higher than 75 km/h. In such case, the distance between two consecutive measurements is around 12 meters, so that it is possible that the illuminance decrease was so high that the source was simply ignored. With such a large distance between points, the validity of an almost constant angular emission function is clearly faulty anyway. Actually for such a reason, we suggest to limit the driving speed to around 25 km/h when performing a lighting device inventory with the LANcube. At 25 km/h the distance between points is about 4 m.

For the determination of the height of the lighting system, we generally overestimate the real height (see Table 2). The overestimation is higher for LED than for HID system and this is clearly because of the very different emission functions. Apparently the HID meets in a better way the assumption that the angular emission function is constant. There is no obvious way to correct that overestimation except if the further experiments shows that the overestimate is very well linked to the lighting technology. We do not have enough data to confirm this yet.

The success in spectral type recognition is high. We confused only one source out of 74 ( $\sim 1\%$ ). We detected one HPS as a 3000K LED. HPS detection is a challenge since the very large dispersion in the 3D color space (see Figure 2). Moreover 3000K LEDs are next to the HPS region of the color space. We were probably sampling a specially white HPS lamp. For that reason, we need to sample more HPS lamps to improve the spectral recognition table 1.

We succeed in detecting asymmetric sources like wall packs installed on building facades perpendicular to the road along with billboards. Car headlights and spotlights are detected by

**Table 2.** Detection statistics for lighting devices higher than 4 m within 15 m from the road. We considered mainly the street lights and some private industrial lights in Saint-Camille and Stoke.

Parameter	Value	Percentage
Sources detected	73/74	98.6%
Not detected	1/74	1.4%
False detection	0	0%
Spectrum recognized	73/74	98.6%
Height error >200%	4/74	5.4%
Averaged height error and standard deviation	HID cobra LED	+21%±32% +53%±50%

the LANcube but the determination of their distances and then of their fluxes is completely off the reality. This is because that their angular function is far from constant, so that we systematically overestimate their distance by about 1 order of magnitude. Such a large distance combined with a normal illuminance detected end up in fluxes about 3 orders of magnitude too high. For the moment, we exclude these tremendous fluxes from the extracted inventory.

## 5. Conclusion

In this paper, we suggest a new method to determine the lighting devices inventory of a region out of the data acquired with the LANcube v2 radiometer. The method can detect ~99% of the high flux sources (e.g.  $\approx 1000$  lumens) located within 15 m from the road. The method also detects small flux sources like residential bulbs as long as they are not too far from the road. That method offers the advantage to detect also private lights that are never included in public lighting inventories. The method is very efficient to recognize the spectral type of each lighting device. On the other hand, the method generally overestimates in average the lamp heights by 21 to 53 percent, depending on the angular photometry of the lamp. It most probably also overestimates the associated lamp fluxes. The height overestimate is the direct consequence of one basic assumption of the method that the angular emission function of the sources is constant between two consecutive detection points. Errors in detection may also happen because of the presence of smooth obstacles like tree leaves. For that reason we recommend to perform LANcube inventory in Autumn when the leaves have fallen. The proposed methodology does not allow the correct determination of the distance of spotlights because of their highly variable and focused angular emission function.

Despite the problems associated with this method, we believe that it constitutes a powerful tool for the study of ALAN and its effects. Its application is not restricted to roads and streets. As an example, the LANcube may be attached to a helmet so that a pedestrian or a cyclist can record with very high accuracy the ALAN and even in places inaccessible to cars.

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