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A proposal for characterizing global light pollution using a LEO nanosatellite

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***Abstract*—Solid-state lighting (LED lighting) is an energy efficient alternative to conventional sodium, mercury and fluorescent outdoor lighting. The high spectral density of blue light emitted by nominally "white" LEDs has in recent years become an ecological and health concern. Monitoring the global presence of LED lighting as a fraction of total light pollution has hence become a parameter of interest to government organizations dealing with health and environmental protection. This work describes a planned low-earth orbit satellite mission with a low-cost technology and algorithms to provide light pollution images and estimates of the contribution of solid-state lighting relative to conventional illumination globally.**

***Index Terms*—Nanosatellite Earth observation, light pollution, spectrally-resolved light measurement.**

I. Introduction

Large fraction of Earth's population lives under light-polluted skies. Artificial lights overpower the darkness and the city skies glow at night, disrupting the natural day-night pattern and shifting the delicate balance of our environment. The negative effects of the loss of natural darkness are (*i*) the disruption of the ecosystem and wildlife, (*ii*) harming human health through disruption of the circadian rhythm [1], (*iii*) the disruption of astronomical observation [2] and finally (*iv*) wasted energy in illumination. The public concern about light pollution is rising as a growing number of scientists, homeowners, environmental groups and civic leaders are taking action to restore the natural night [3].

The purpose of this work is to describe a proposed nanosatellite mission to evaluate global light pollution and to determine, if possible, the global progress in solid-state lighting from space. Light pollution is generally monitored from Earth [4], [5] (see an example in Figure 1), while with the progress in satellite-based Earth observation, light pollution maps of the entire world are now available on the internet [6] (illustrated in Figure 2).

Solid-state lighting is being implemented worldwide as the alternative, more efficient and less toxic, light source (relative to mercury containing lamps) [7]. The key advantage of solid-state lighting, besides the low toxicity and size, is in that it offers a light source with luminous efficiency comparable to that of conventional outdoor lighting at a significantly better color rendering index (CRI) [1]. For example, a nominally-white LED bulb with CRI ≥ 80 can be obtained with luminous efficiency $\eta_\nu = 90$ lm/W, while a low-pressure sodium (LPS) bulb will have luminous efficiency of $\eta_\nu = 160$ lm/W. However, the LPS emits light in a single yellow line at 589 nm and therefore has a very poor color rendering index (CRI $= -44$). Note that a modern halogen lamp in E27 base with CRI = 100 will have $\eta_\nu \approx 17$ lm/W.

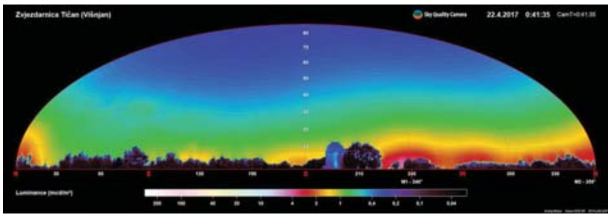

Fig. 1. Light pollution seen in west-pointing night photograph of Tičan observatory in Višnjan (Istria, Croatia), which shows light pollution coming Trieste/Italy at 360 degrees and from Poreč/Croatia at 240 degrees. Image taken by EOS Nikon Sky Quality Camera by Andrej Mohar, printed with permission.

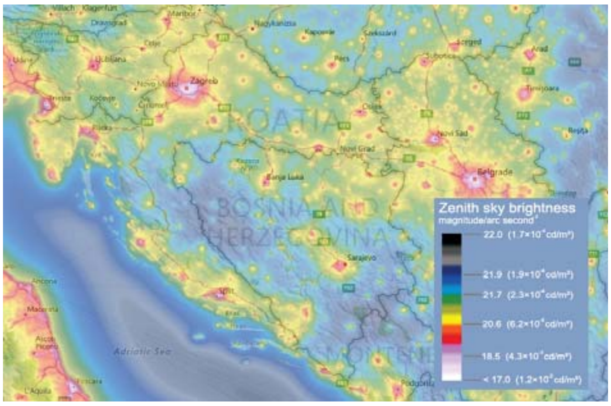

Fig. 2. Global light pollution map available on the internet [6].

Luminous efficiency η_ν is a measure of the efficiency of conversion of electrical energy (Watts) into luminous flux (lumens) and can be easily computed for any light source/bulb by dividing the luminous flux specified for the light bulb by the electrical power it consumes. Luminous efficiency η_ν is measured in lm/W, but is not to be confused with luminous efficacy K (also measured in lm/W) which characterizes the shape of the light emission spectrum. The relationship between these quantities is given with $\eta_\nu = \eta_e \cdot K$, where η_e is the efficiency of the device to convert electrical enegy into radiant flux (measured in W) [7].

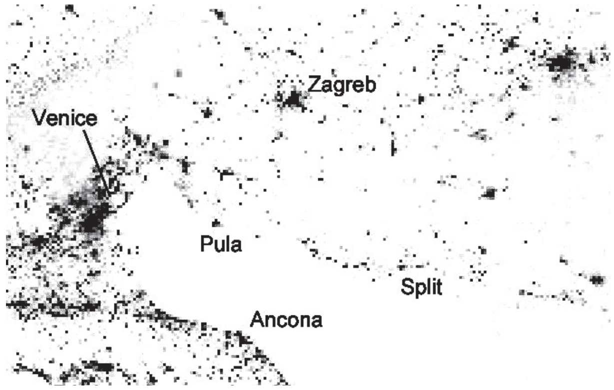

Fig. 3. Night-time light emission from Croatia and Italy taken April 14, 2019 in day-and-night band between 500 do 900 nm. The gray-scale image has been inverted to negative image and contrast increased to show dark where there is light and white where there is no light emitted (VIIRS).

Nominally white light-emitting diodes generate a combination of blue and yellow light that appears to the human eye as white of differing degree of "warmness". These light-emitting diodes are built as blue gallium-nitride-based LEDs emitting at ≈455 nm covered with a layer of yellow phosphor (peak of emission ≈590 nm) so that the blue light from LED excites the phosphor and the LED generates a combination of blue and yellow light. Phosphor is a chemical compound that emits light in a certain wavelength range when illuminated with light of shorter wavelength. The color of nominally white LEDs, marketed as "warm white" or "cool white", is controlled with the ratio of the power in the yellow relative to the blue part of the LED emission spectrum: more blue in the spectrum appears as colder white light.

Correlated color temperature (CCT) is a measure of a light source's color appearance defined by the proximity of the light source's chromaticity coordinates to the blackbody-emission locus, as a single number rather than the two required to specify a chromaticity [1]. The spectral power distribution of a blackbody radiator can be completely determined from its absolute temperature using Planck's radiation law. Practical light sources of different power spectral densities but identical chromaticities will also have identical CCTs. An incandescent light bulb with a tungsten filament may have a CCT of 2700 K, which can also be approximated with a "warm white" LED. Although an approximation, CCT is simple way to communicate the color appearance of a light source. However, it neglects that fact that two sources with same CCT may have vastly different emission spectra.

New regulations are being put in place worldwide to control light pollution while cost per lumen of solid-state light sources is reducing. As a result we expect to see conventional lighting, such as metal halide, mercury and sodium lighting reduce in time and solid-state lighting progress.

II. Earth light captured in space

Night-time images of cities and lighting from space have been available since the 1970-ies [8]. More recently, the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor launched in 2011 started providing high-quality night-time images of the Earth in the day-and-night band (DNB) 500 nm and 900 nm wavelength range with intensity resolution of 14 bits. A night-time image of a portion of Croatia and Italy downloaded as part of this work is shown in Figure 3.

In 2010, photographs from the International Space Station showed that cities around world appear to be lit by lighting of different color: images from space reported in [9] show that Tokyo appears blue-green resulting from mostly metal halide lamps, while Los Angeles and Las Vegas appear more yellow resulting from sodium lamps. The fact that these images were captured on a regular CCD camera, raised the question whether one could use a regular camera to determine the type of light source generating the light pollution [10] and has initiated this satellite mission: to estimate the fraction of LED lighting in the overall emission from the Earth using a CCD camera or a miniature spectraphotometer.

The objective of this work is to use satellite-based Earth observation to monitor, over a period of time, the fraction of solid-state lighting in the overall illumination in the world. Our approach is to acquire spectrally resolved night-time images of the Earth using a CubeSat, analyze the data and determine the fraction of the overall illumination that originates from solid-state lighting globally and locally in Croatia. To this end we first measure and discuss the emission spectra of nine different conventional and solid-state lighting sources. All of the presented discussion is preliminary and is subject to change once the optimal algorithm and hardware approach to reach the target functionality is identified.

III. Light-source emission spectra

We measured the emission spectra of representative bulbs for light-sources used in public illumination. They are listed in Table I.

TABLE I
Light sources characterized (all E27 base)

Code	Description	Power	CCT
HPS	High-pressure sodium	70 W	
MH3	Metal-halide	150 W	3000 K
MH4	Metal-halide	150 W	4000 K
HG	Mercury vapor	125 W	
LED3	806 lm, CRI>80	9 W	3000 K
LED4	806 lm, CRI>80	9 W	4000 K
LED6	806 lm, CRI>80	9 W	6500 K
LED0	1000 lm, CRI 90	11 W	2700 K
CFL	900 lm, CRI > 80	15 W	2700 K

The emission spectra were measured using Photon Control SPM002-CH spectraphotometer with < 0.6-nm resolution and spectral range between 350 nm to 1000 nm in

Fig. 4. Three of the discharge lamps tested, from left to right MH3, HPS, and HG bulbs.

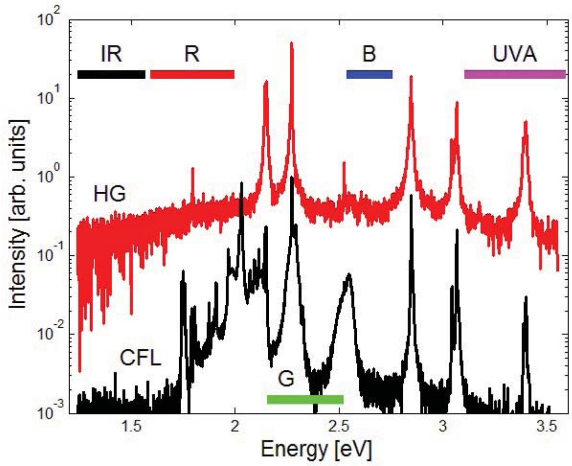

Fig. 5. Mercury bulbs, top shows mercury vapor high-intensity discharge bulb "HG", bottom graph shows compact fluorescent E27 bulb "CFL"

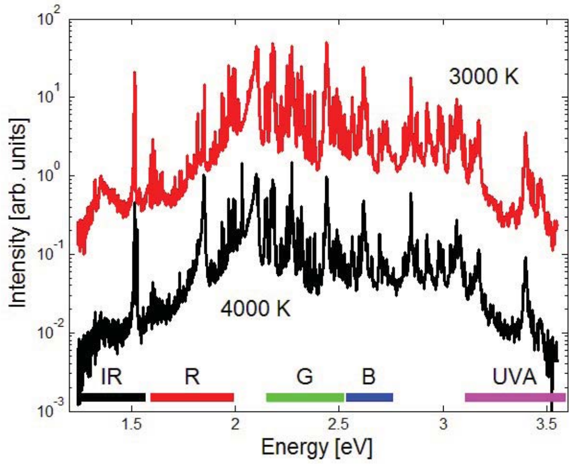

Fig. 6. Metal halide emission spectra: top chart has CCT = 3000K "MH3" and bottom chart CCT = 4000K "MH4".

3560 pixels. The room in which measurements were done was dark and to reduce the noise in the measurement, we averaged 600 one-second scans for each bulb. The warm-up of each lamp was visually observed and measurements were taken after approximately 30 minutes after turn-on.

The measurements of emission intensities for all light sources are shown in Figures 5, 6, 7, and 8. The power spectral density is shown versus energy and on a logarithmic scale to accentuate the shape of the peaks in the emission and show how much they are above the noise. The intensities of various sources shown in the Figures have been normalized and shown in a logarithmic graph to reveal correlations in the emission peaks, hence, one should not associate the vertical value with the actual lamp intensity. To assist simple conversion to wavelength (more commonly used in illumination), the wavelength regions of near infrared (IR), red (R), green (G), blue (B), and soft ultra-violet (UVA) light are also shown. The boundaries between R, G, and B are taken from [7].

A. *Conventional light sources*

The measurements of emission power spectral density of conventional lighting sources (metal halide, mercury and high-pressure sodium lamps) are shown in Figures 5, 6, and 7.

Mercury is the staple metal of conventional high-intensity discharge and fluorescent lamps with high luminous efficacy. Excited mercury vapor emits strongly in the ultraviolet spectrum and is then efficiently used to excite a phosphor to downconvert the energy into the visible part of the spectrum. The emission spectra for a mercury vapor lamp "HG" and a compact fluorescent lamp "CFL" are shown in Figure 5. Inasmuch as both bulbs are based on mercury vapor to generate the ultraviolet light and appear to use similar phosphor, the correlation between the spectra is $C = 0.58$.

Metal halide lamps are also based on mercury discharge to generate the ultraviolet light, but metal halides are mixed in with the mercury vapor to produce a wide variety of lines as shown in Figure 6 and can hence be adjusted to have "warm" or "cool" white tint. The top and bottom graphs correspond to the "MH3" and "MH4" bulbs, respectively. The correlation between the two spectra is $C = 0.85$. The difference from unity is the manifestation of a different CCT. The emission spectra of the metal halide lamps is rich with emission lines and hence gives a color rendering index acceptable for outdoor lighting (CRI > 65).

It is worth noting that, as shown in Figures 5 and 6, both metal halide and mercury vapor lamps emit some energy in the UVA region (315-400 nm). This portion of the UV spectrum is not absorbed by the ozone layer and therefore these spectral lines may be detectable from space.

High-pressure sodium lamps (HPS) contain mercury vapor with traces of inert gas, such as, xenon. They have a distinct yellow/orange tint to them resulting from majority of the emission coming around 589 nm, characteristic of sodium. The bottom graph in Figure 7 illustrates the emission spectrum. Low-pressure sodium lamps (LPS), not measured in this work, has only sodium vapor and only two lines: the dominant emission at 589 nm and smaller

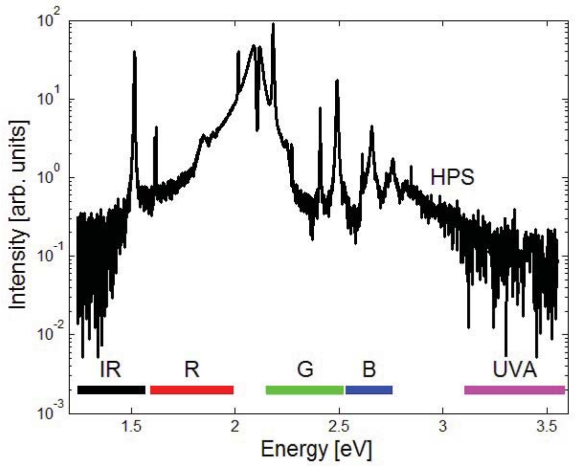

Fig. 7. High-pressure sodium lamp emission spectra.

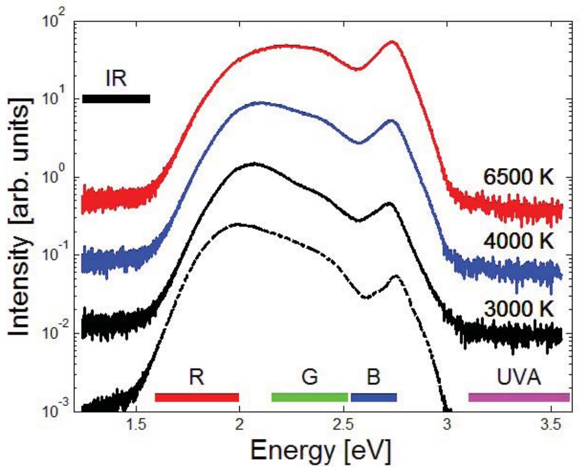

Fig. 8. Four nominally white light-emitting diode spectra. All bulbs are small household bulbs that fit into E27 base. From top to bottom we have CTT = 6500 K, CCT = 4000 K, CCT = 3000 K, and finally, CCT = 2800 K. The last (dashed line) is a houselhold lamp with CRI > 90

emission at 819 nm.

B. White light-emitting diodes

The CCT of nominally white light-emitting diodes is adjusted by controlling the thickness and type of phosphor deposited onto blue light-emitting diodes. The imperfect phosphor thickess control produces a spread of correlated color temperatures in the production process mandating product binning. Figure 8 show the spectra of four nominally white light-emitting diodes with different correlated color temperatures: the ratio between the intensity of the 2.75-eV blue peak (455 nm) and the yellow/orange peaks ranging from 2.20 eV (621 nm) to 2.25 eV (554 nm) increases with the CCT.

The high color-rendering index of LEDs comes from the fact that the yellow and blue spectra are continuous and smooth rather than exhibiting peaks like high-intensity discharge lamps. The LED emission spectra are very similar regardless of the CCT value: the correlation coefficient between 6500 K and 4000 K units is $C = 0.94$, between the 4000 K and 3000 K units $C = 0.97$, and between the 6500 K and 3000 K units $C = 0.83$.

C. Light source identification problem

The spectrum of night-time lights coming from the Earth is a mixture (an incoherent linear superposition) of many light sources. The photon flux from each of the light sources is first reflected from the ground surface with a magnitude reflection coefficient $R(E)$ that depends on the surface structure, angle of incidence and energy, and then transmitted through the atmosphere to the satellite. The transmission through the atmosphere is quantified with the transmission coefficient $T(E)$. The reflection spectrum $R(E)$ will be different for every installed light fixture, but for simplicity it makes sense to assume that $R(E)$ is a slow varying and smooth function of energy and that it represents an average over the angle of incidence and surface quality. Note that most of public illumination is installed over urban pavement and that an estimate of $R(E)$ can be determined experimentally. The transmission $T(E)$ can be determined from publicly available sources.

The spectra $P(E)$ (power spectral density) detected by the satellite may therefore be approximately written as,

$$P(E) = T(E) \cdot R(E) \cdot \sum_{k=1}^{n} c_k P_k(E) \quad (1)$$

Here c_k is the power contribution of lamp type k in the view of the measurement equipment (e.g. camera pixel), while the number of possible emission sources is n. The task is to determine the c_k's with known $P_k(E)$ power spectral density for each lamp. If the power spectral densities of the sources $P_k(E)$ were orthogonal, this would be a relatively simple task, but the spectra exhibit a high degree of correlation as we confirmed in Figure 9. The bar graph in Figure 9 shows that the correlation between the 4000 K LED emission spectra and the other LEDs is high, but that the correlation with CFL and HG lamps are not small, which is what we would like to be able to extract one from the other. The lowest correlation is found between the LED4 and the HG mercury lamp. Clearly, a more sophisticated method for identifying the light source will have to be applied.

The analysis of commercially-used lamp emission spectra with the goal to identifying the type of light source from the emission has been successfully implemented by [10]. Their approach was to filter the spectrum captured from a mixture of lights into bands and the integral power in each band was used in a statistical correlation analysis to obtain the type of source with a certain confidence level. As we have seen in Figure 9, the fundamental difficulty in extracting the light-source type and hence the need for sophisticated statistical analysis stems from the fact that individual light-source emission spectra, and there are many, do not form an orthogonal set.

Another approach is to search for markers in the emission spectra. For example, low-pressure sodium (LPS) bulb has a strong emission at 589 nm and could be used to determine what fraction of the light is coming from LPS

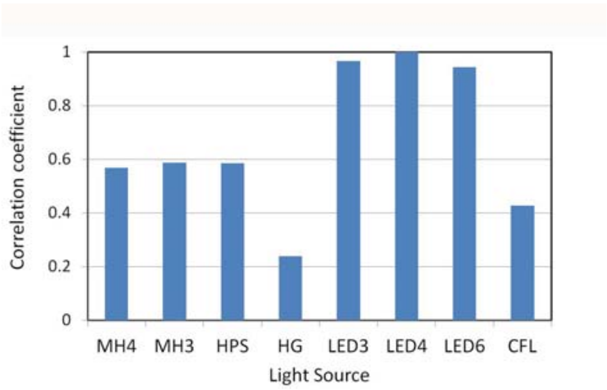

Fig. 9. The correlation coefficient between the LED4 and the selection of other sources.

by simply measuring emission strength in narrow bands below, around, and above the targeted marker and looking at the ratio of the three measured parameters.

A further difficulty arises from the product variability: not all metal halide, CFLs, and mercury vapor bulbs are the same. They vary between manufacturers and since their spectra depend on the chemistry of the halides and the phosphors, the emission spectra varies. As it is not clear how severe the variability is and this needs to be determined experimentally by collecting data on the light pollution spectra on the Earth and analyzing it to possibly develop an algorithm that will be imune to chemistry variation.

Finally, the spectral range of data collection is set to not wider than 350 nm to 1000 nm which can be accomplished with a silicon detector. An in-depth study of the spectra with a successful algorithm for identifying the type of light source was published by [10] and in that reference the authors made measurements with a spectrometer between 350 nm and 2400 nm, while the conclusion was that the wavelength range between 350 nm to 1000 nm is sufficient to reveal the spectra differences and identify the type of light source.

IV. Conclusion

Monitoring total light pollution from space has been active since the 1970-ies. The introduction of solid-state lighting and its associated blue-yellow emission spectrum have caused its own set of environmental concerns. Performing spectrally resolved night-time imaging of Earth is potentially a good approach to quantify the progress of solid-state lighting and light pollution on a global or local areas.

In this work we have shown measured emission spectra from conventional and solid-state light sources that one expects to see from space and discussed two potential approaches to detecting the origin of light pollution using spectrally resolved images from space.

V. Acknowledgement

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