FM 21:
Mitigating Threats of Light Pollution & Radio Frequency Interference

https://doi.org/10.1017/S1743921316003574 Published online by Cambridge University Press

Astronomy in Focus, Volume 1, Focus Meeting 21
XXIXth IAU General Assembly, August 2015
Piero Benvenuti, ed.

doi:10.1017/S1743921316003574

Session 21.1 – Observations, Advances in LED Technology, and Dark Sky Protection

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Abstract. The importance of dark sky protection, potential threats to further degradation from LED technology, the announcement of a new world atlas of artificial night sky brightness, and the use of color images from the orbiting International Space Station for monitoring potential sources of light pollution were discussed in the six talks of this session. It was clear from the presentations that the work of professional astronomy depends upon continued restraint in the use of outdoor lighting, especially new LED technology, which relies upon blue-rich sources to support the advantages of high luminous efficacy and resulting energy savings.

Keywords. techniques: photometric, atmospheric effects, radiative transfer

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1. The search near Near Earth Objects — why dark skies are so important

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The Pan-STARRS telescopes located on Haleakala, Maui, Hawaii, and the Catalina Sky Survey, located near Tucson, Arizona, continuously search for Near Earth Objects (NEOs). Such objects may present a threat to Earth, especially if undetected before entering the atmosphere. These objects are very faint, therefore early detection requires broad passband detectors to maximize the amount of light and signal to noise. The addition of any amount of artificial sky glow between 420 and 820 nm will hinder the search. ue In addition to the Maui and Arizona search telescope locations, follow up telescopes, spread across the planet, play a crucial role in the verifying and determination of accurate positions to establish and orbit. Only then can it be determined whether or not the object poses a threat to Earth. The majority of these followup telescopes are at locations that are impacted by light pollution, and this seriously impacts their ability to secure additional observations.

The evidence of past NEO impacts on the earth's surface, such as Meteor Crater in Arizona (a relatively small object) and the much older Chicxulub crater near the Yucatán Peninsula, estimated at 66 million years ago, are reminders of the potential consequences of these objects. Effects include a cloud of super-heated dust, ash and steam, dust covering the whole Earth, global earthquakes and volcanic activity, and possible mass extinctions.

The Pan-STARRS telescopes, two 1.8-meter diameter instruments at Haleakala Observatory, are the largest digital cameras in the world, surveying large blocks of sky with a sequence of images separated by about 20 minutes (Figures 1a, b, c). The gigapixel cameras collect 3 terabytes of data per night which is subsequently processed looking for moving objects among the stars. To date, almost 13,000 Near Earth Asteroids have been discovered by both Pan-STARRS and the Catalina Sky Survey, of which almost 1600 are classified as potentially hazardous asteroids.

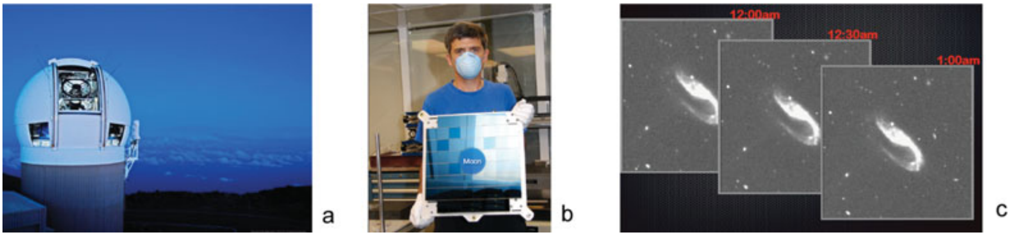

Figure 1: (a) The PanSTARRS telescope atop Haleakala, Maui, Hawaii, (b) the sensor of the gigapixel camera used on the 1.8 meter telescope, and (c) sample sequential images used to detect Near Earth Objects.

Once an object is determined to exist, follow up observations by telescopes across the globe contribute to efforts of orbit determination. Many are affected by light pollution, decreasing the effectiveness of observing programs. In addition, cloudy weather at professional observatory sites may necessitate the observations being taken by amateur instruments from more urban locations. Continuing strong efforts to protect the dark night sky from light pollution are essential for the search for Near Earth Objects, and for mitigating the threat that they pose.

2. LEDs/ALAN—Working to be Good Neighbors

AUTHOR: Robert Adams (CW-Energy Solutions, Paradise Valley, Arizona, United States)

ALAN (Artificial Light at Night) and LEDs have recently become major discussion topics in the areas of astronomy, light pollution, endangered species and human health to mention but a few. In years past, MH, LPS and HPS dominated night lighting with LPS and its associated narrow spectrum as the preferred source around observatories and shorelines. LEDs offer the ability to modify the spectrum, realize substantial energy savings and other associated benefits while meeting the requirements of the astronomy community. The primary concern of the different groups relates to blue light content of the LED. For astronomers, the molecular (Raleigh) scattering related to the blue light interferes with certain portions of the spectrum used for deep space studies. Blue light in the environment also has an impact on sensitive species, such as leatherback turtles and bats, and on the human circadian rhythms.

The spectral power distribution (SPD) of various light sources and the CIE color chart (X,Y coordinates) adequately describe the quality of light emitted and identify potential concerns. The luminous efficacy of the source in lumens/watt is also important. Figure 2 illustrates various types of LED lights including filtered 3000K warm white, both warm white and traditional cool white LEDs with various filters attached, phosphor coated (PC) amber LED, and narrow beam amber, which show promise for meeting outdoor lighting needs while protecting night skies and the environment. It is evident that the metric CCT is not adequate for specifying the new LED solutions with the modified spectra. Percent blue, percent blue and green, XY coordinates, or scotopic to photopic (S/P) ratio are better metrics.

The status of the technology indicates that it is mature enough for wide application, 10,000 new lights are being installed on the roadways of the County of Hawaii over the next 18 months. The efficiency of the lighting has improved 80% over the past three years from 55 lumens per watt to 100. In order to be competitive, efficiency should be

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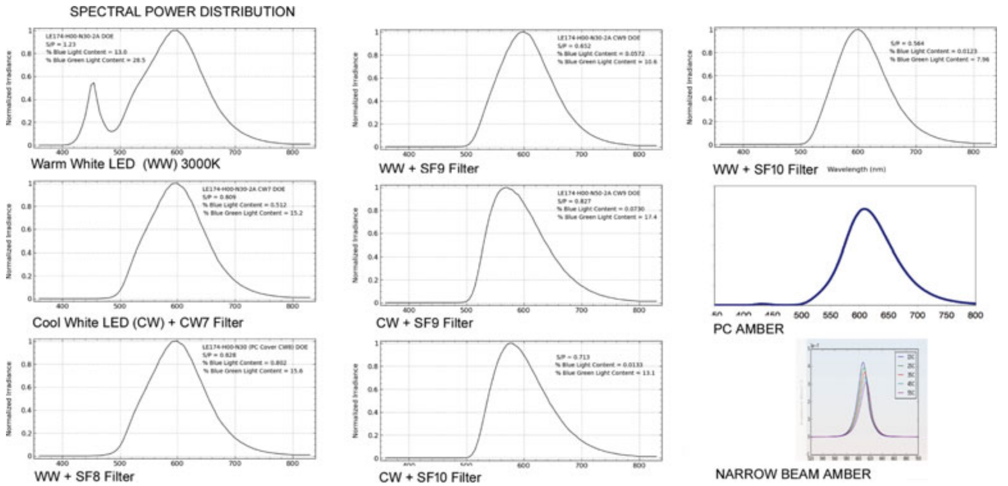

Figure 2: Spectral power distribution of selected LED lamps.

maintained at 70 to 80 lumens per watt. Three new families of filters have been developed and one family qualified for use in the Canary Islands.

Today, lighting plans and implementation are all too often based on opinions and limited data. The ensuing problems and repercussions make it imperative to collect accurate and thorough information. Data collection is now ongoing using a variety of techniques analyzing the "before" and "after" lighting results from the County of Hawaii LED streetlight conversion. The studies will focus on any quantifiable impact LEDs may have on such topics as light pollution, endangered animals, astronomy and most importantly, the citizens of our local communities.

3. Light emitting diodes and astronomy — a change for restoration of the dark night sky or for further loss

AUTHOR: Richard Wainscoat (Institute for Astronomy, University of Hawaii, Honolulu, Hawaii, United States)

Across the planet, conventional light sources such as high pressure sodium, are rapidly being replaced by light emitting diodes (LEDs). As light fixtures are being replaced, there is a tremendous opportunity for restoration of dark night skies through replacement of poorly shielded fixtures by fully shielded fixtures. Also, the huge advantage that LEDs offer is that the light from and LED is much easier to direct, allowing the use of less lumens for a given task. However, it is critically important to limit the amount of blue light from the LEDs.

Sales people are strongly promoting LEDs with high correlated color temperature (CCT), such as 5000K. They are promoting them on energy efficiency grounds - higher energy efficiency is easier to sell. These LEDs have tremendous amounts of blue light near 450 nm. The photopic human eye is relatively insensitive to this blue light, but the dark adapted scotopic eye is much more sensitive, and CCDs are also very sensitive to this wavelength of light. As a consequence, both professional and amateur astronomers are very seriously impacted by high CCT LED lighting. The sodium lighting that the LEDs are replacing has relatively little blue light. Blue light is strongly scattered by air molecules in the atmosphere. There is little reason to install LEDs with high blue light content now because there is only a 5-7% difference in energy efficiency between 3000 K

Figure 3: Skyline of the city of Honolulu, Hawaii, at night.

and 5000K white LEDs. Use of high CCT LED lighting will cause further deterioration of night sky quality.

In contrast, use of LED lighting with low CCT (e.g., 2400K or 2700K), or use of filters to remove the blue light, can restore the dark night sky. LED lighting is much easier to direct, meaning that an area such as a roadway can be lit with many less lumens with LEDs compared to conventional lights such as high pressure sodium. And use of fully shielded fixtures will eliminate direct uplighting. Figure 3 illustrates part of Honolulu as it is currently lit at night, with an estimated 30 million lumens directed upwards resulting in a waste of approximately $300,000 per year in energy costs.

4. Advanced strategies for outdoor LED lighting applications and technologies to curtail regional light pollution effects

AUTHOR: Christian Monrad (Monrad Engineering, Tucson, Arizona, United States)

LED lighting systems for outdoor lighting applications continue to evolve as do strategies to mitigate related effects upon regional astronomical and ecological assets. The improving availability and relative lumen-per- watt efficiencies of blue-suppressed low correlated color temperature emitters, narrow band amber, phosphor converted amber, and various combinations of broadband emitters and sub-550NM and sub-500NM filters allow for a wide palette of choices to be assessed to suit site-specific and task-specific lighting needs. In addition to static spectral content options, readily available luminaire designs also include precise geometric beam shape selections and adaptive controls to include dimming, dynamic spectral shifting, motion detection, and dynamic beam shaping to minimize total environmental lumen emissions throughout the course of the nighttime hours.

Major motivators for large scale replacement of metal halide, high pressure sodium, and low pressure sodium lamps with LEDs are reduced maintenance, energy savings, and many HID lighting systems reaching the end of their life. This, and the factors listed above, makes now a good time to modernize. There is an efficient, cost effective and properly shielded LED replacement for almost every legacy lighting system.

Regional and international light pollution mitigation regulations are inconsistent. For example, in Chile near major observatories a maximum output of 15% of the total in

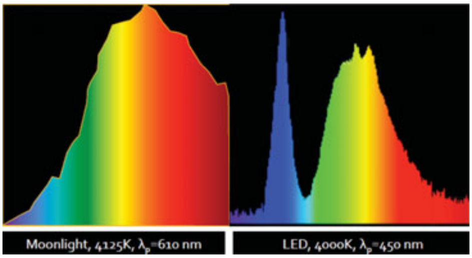

Figure 4: Comparison of the spectrum of moonlight (left) and 4000K LED lamp (right).

Figure 5: Scene illumination from 3000K LED lamps at Tucson International Airport.

sub-500 nm wavelengths is prescribed, in Cohise County, Arizona, USA, at specification of maximum CCT of 3000K is employed, in Pima County, Arizona this value is 3500K, while in the Canary Islands a maximum of 25% sub-550 nm is used. Of these, the use of CCT is archaic and inappropriate for many LEDs, since it is based upon a Plankian blackbody radiator. Scotopic to photopic (S/P) ratio is a better metric. Some advertisers claim that 4000K is "natural moonlight" but with the spectral power distribution of most LED lamps rated at this CCT, the percent blue and S/P ratio are quite different (see Figure 4), and natural moonlight is close to a 2200K CCT LED lamp. Not only is S/P ratio available as part of the CIE/IES testing format, it can be field verified with a handheld spectrometer.

Of the LED technologies available today, narrow band amber LED has the lowest S/P ratio at 0.3 (see bottom illustration in Figure 2). An LED with a CCT of 3000K typically will result in and S/P ratio of 1.3, with cooler (higher CCTs) colors producing even greater ratios. Filtered LEDs provide a method of reducing the S/P ratio to below 1.0. For comparison, low pressure sodium and high pressure sodium have typical S/P ratios of 0.23 and 0.54, respectively. With the improved aiming characteristics of LED luminaires, often very significant reductions in the amount of light compared to HID systems may be realized in a re-design. For example, at Tucson, Arizona, USA international airport, airline terminal parking area outdoor lighting was replaced, converting from 22 megalumens (primarily HPS) to 6 megalumens 3000K LED (Figure 5). Even after accounting for the increase in S/P ratio, there was a 26% reduction in downward looking luminance. This installation is expected to result in skyglow reduction, energy savings, and lowered maintenance costs.

5. The new world atlas of artificial sky brightness

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The main steps toward the completion of the new World Atlas of Artificial Sky Brightness (WA II) have been realized, and a whole earth zenith sky brightness prediction has been computed. The upward radiance data used are those from Visible Infrared Imaging Radiometer Suite (VIIRS) Day-Night Band (DNB) on board the Suomi NPP satellite. The use of this newly available radiance data allows for an increased real resolution, even while maintaining the same 30×30 latitude and longitude pixel size. The computational technique has been updated, in comparison to the first World Atlas, to take into account

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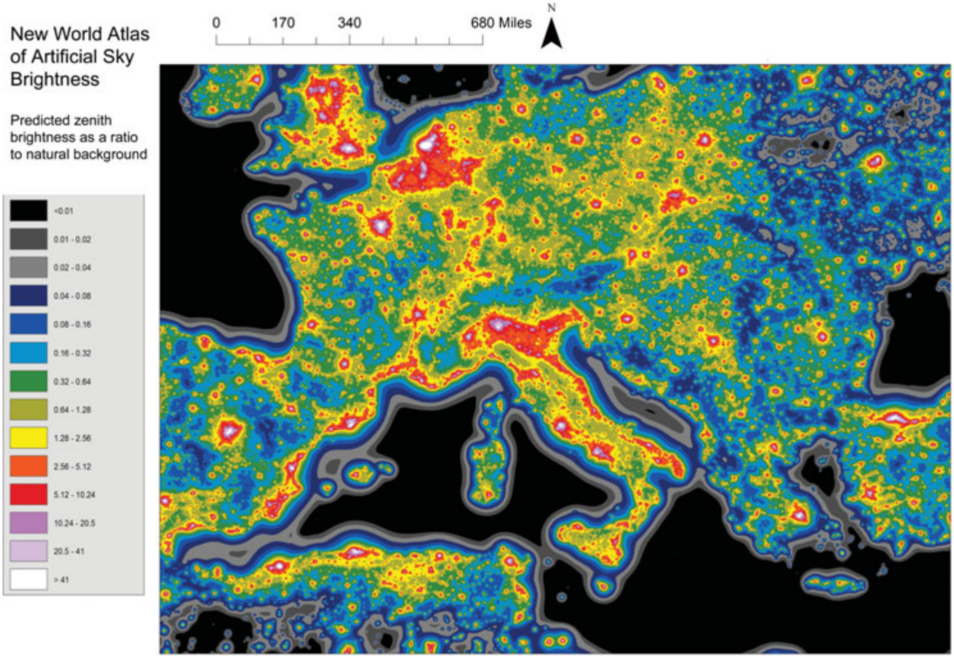

Figure 6: Artificial sky brightness at zenith prediction for south-central Europe from the new World Atlas.

both sources and sites elevation. The elevation data are from USGS GTOPO30 global digital elevation model, with the same pixel size as the WA II maps.

The upward emission function used to compute the Atlas is a three parameter function, representing three different upward patterns: Lambertian reflection, high zenith angle emission typical of direct emission from "cobra head" streetlights, and an emission pattern at moderate zenith angles. The parameters are then constrained to Earth based night sky brightness measurements, primarily from SQM-L devices, using a database of tens of thousands of measures from sources world-wide. In this way we use a global fitting upward function for the final map's calibration.

We maintained constant atmosphere parameters over the entire Earth, identical to those used for the first Atlas (Garstang atmospheric clarity coefficient k=1, equivalent to a vertical extinction at sea level of 0.33 magnitude in the V band). This was done in order to avoid introducing a local bias due to different conditions that may confound the light pollution propagation effects.

The VIIRS DNB data used for the input data were chosen from the months ranging from May to September 2014 in order to avoid introducing bias from the variable snow coverage in mid to high northern latitudes. In the southern hemisphere this problem is far less pronounced.

The final maps demonstrate greater detail and resolution than the first world atlas. Figure 6 shows a close-up of south-central Europe. The predicted artificial sky brightness is shown as a ratio to the natural background, which is assigned at 22.0 V-magnitudes per square arc second or 172 micro-candela per meter squared. The completion of the project will include estimates of the percentage of the population of the earth residing in each of five separate classes of night sky degradation. The atlas should provide a useful tool for urban planners, professional and amateur astronomers, protected area managers, and the general public seeking locations from which to enjoy as natural a night sky as possible.

6. ISS images for observatory protection

AUTHORS: A. Sánchez de Miguel (CEGEP de Sherbrooke, Sherbrooke, Québec, Canada), J. Zamorano (Astrofísica y CC. de la Átmosfera, Universidad Complutense de Madrid, Madrid, Spain), M. Aubé, J. Gallego.

Light pollution is the main factor of degradation of the astronomical quality of the sky along the history. Astronomical observatories have been monitoring how the brightness of the sky varies using photometric measures of the night sky brightness mainly at zenith. Since the sky brightness depends in other factors such as sky glow, aerosols, solar activity and the presence of celestial objects, the continuous increase of light pollution in these enclaves is difficult to trace except when it is too late. The use of direct light detection from above the earth's surface is up to 14 times more sensitive than sky brightness measurements due to the natural variations. Also, tracking trends in the artificial light sources is important to night sky protection efforts.

Using models of light dispersion on the atmosphere one can determine which light pollution sources are increasing the sky brightness at the observatories. The input satellite data has been provided by DMSP/OLS and SNPP/VIIRS. Unfortunately, their sensors are in panchromatic bands which have little or no sensitivity to blue wavelengths. Therefore they are not useful to detect potential increases in upward emissions due to the dramatic change produced by the irruption of blue-rich LED technology in outdoor lighting. The only instrument in the space that is able to distinguish between the various lighting technologies are the DSLR cameras used by the astronauts onboard the ISS. This is because their sensors contain three channels, R, G, and B.

The objectives of this work are to contribute to knowledge of upward emissions for use in sky brightness models, develop methods to calibrate satellite measures of upward radiance to an absolute scale, and identify trends in spatial, temporal, and spectral variation of light pollution sources and their relationship with the sky brightness variations. Through the use of both remote sensing and ground based observations, and the identification of associated relationships between the two classes of observations, a more comprehensive evaluation of world-wide impact from light pollution is obtained.

The examination and evaluation of the remote sensing data, from earth observation satellites and ISS DSLR images, revealed that while it is possible to detect the presence of artificial light sources, they were not designed primarily for measuring radiances. The main contribution of this study include: 1) Calibration of the DMSP/OLS data from 1992-2010, 2) Evolution of energy consumption in street lighting with satellite data, 3) Absolute photometric calibration of nighttime images of the Earth from the International Space Station (ISS/D3S), and 4) The cataloguing and geo-referencing of the ISS image archive. Examples of upward radiance images of the city of Madrid, Spain, are shown in Figures 7a, b, and c, with sources DMPS/OLS, VIIRS/DNB, and ISS/D3S/RGB, respectively.

The RGB data from the ISS camera allows for the interpretation of the type of light source observed in each image. The amount of light detected by R, G, and B channels from each type of lighting is computed, and the ratio of combinations of the channels in the observation images may be used to infer the lamp type (Figures 8 and 9).

Photometric calibration of the green channel of the ISS camera with reference stars allows for comparison with VIIRS/DNB data. Often such a comparison necessitates allowing for atmospheric extinction and tilt, transmission of the window of the ISS, and

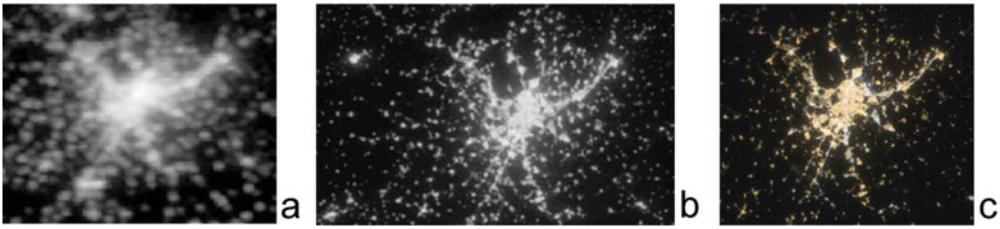

Figure 7: Images of Madrid, Spain from space, (a) DMSP, (b) VIIRS, and (c) ISS.

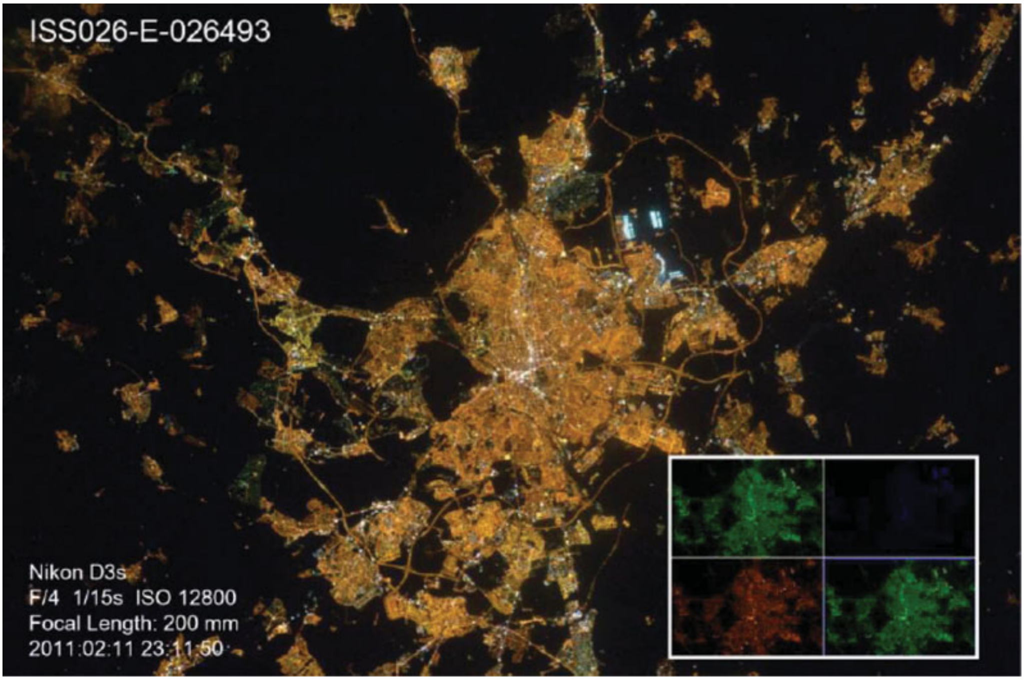

Figure 8: High resolution ISS image of Madrid showing RGB combined and separate channels (inset).

camera linearity. After these corrections are made, a good fit between the two sensors is achieved (Figure 10).

Near an observatory, emitting sources may be identified in ISS images and their spectra characterized approximately. The manner in which these sources may affect the night sky spectrum may be predicted. Ultimately the prediction of such effects will lead to wise choices in outdoor lighting. We are planning to send an official request to NASA with a plan to get images for the most important astronomical observatories. We ask support for this proposal by the astronomical community and especially by the US-based researchers. See `www.citiesatnight.org`.

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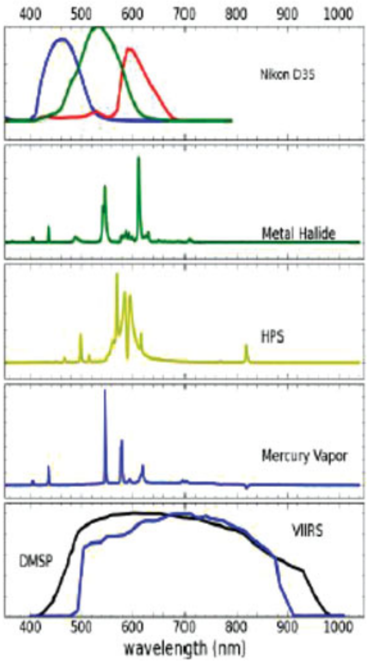

Figure 9: Comparison of senor sensitivity and emission from light sources.

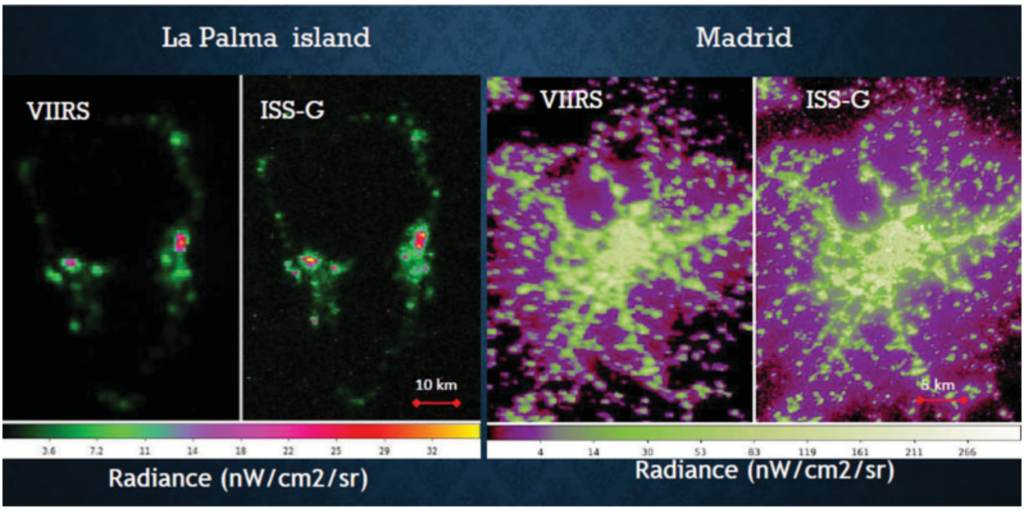

Figure 10: Comparison after calibration of VIIRS and ISS calibrated upward radiance measures.

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