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Ground-based hyperspectral analysis of the urban nightscape

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ABSTRACT

Airborne hyperspectral cameras provide the basic information to estimate the energy wasted skywards by outdoor lighting systems, as well as to locate and identify their sources. However, a complete characterization of the urban light pollution levels also requires evaluating these effects from the city dwellers standpoint, e.g. the energy waste associated to the excessive illuminance on walls and pavements, light trespass, or the luminance distributions causing potential glare, to mention but a few. On the other hand, the spectral irradiance at the entrance of the human eye is the primary input to evaluate the possible health effects associated with the exposure to artificial light at night, according to the more recent models available in the literature. In this work we demonstrate the possibility of using a hyperspectral imager (routinely used in airborne campaigns) to measure the ground-level spectral radiance of the urban nightscape and to retrieve several magnitudes of interest for light pollution studies. We also present the preliminary results from a field campaign carried out in the downtown of Barcelona.

1. Introduction

Light pollution is an issue of growing interest for urban planners, city managers and environmental protection agencies. In its broadest sense, this term encompasses the undesired side-effects associated with the production and use of artificial light, especially at nighttime (Falchi et al., 2011; Bará, 2013, 2014). Excessive or misdirected light leads to unnecessary energy waste and increased greenhouse gas emissions (Gallaway et al., 2010; Kyba et al., 2014), and poses, according to recent findings, non-negligible threats to the nocturnal environment (Hölker et al., 2010; Gaston et al., 2013, 2015) as well as potential health hazards (Cho et al., 2015; Haim and Zubidat, 2015; Stevens et al., 2013).

Making strategic decisions on outdoor lighting policy at local and regional levels requires an accurate knowledge of the actual light emissions, ideally with enough spatial and spectral resolution to allow the identification of individual light sources, their directional emission patterns and their detailed spectral composition (Elvidge et al., 2010).

Urban radiance data with moderate spatial resolution are currently available from several instruments on board of space platforms, such as the historical time series of the Operational Linescan System (OLS) of the U.S. Defense Meteorological Satellite Program (DMSP) (Cinzano and Elvidge, 2004; Elvidge et al., 2013; Yang et al., 2014), the Suomi-NPP VIIRS instrument Day-Night Band (DBN) (Miller et al., 2013), and the Earth images taken with commercial grade cameras from the International Space Station (ISS) (Castiglione et al., 2012). The DMSP and Suomi-NPP satellites, located in near polar orbits at altitudes close to 850 km, provide whole Earth coverage with radiance detection limits of order 5×10^{-10} and 2×10^{-11} W cm^{-2} sr^{-1}, and ground footprint sizes of 5 km and 742 m, respectively. They give no spectrally resolved information, because the detection is performed in a single 0.5–0.9 μm panchromatic band (Elvidge et al., 2013). NightPod-based ISS nighttime imagery (Castiglione et al., 2012), acquired from an orbit at about 400 km altitude with 51.6° inclination and variable footprint pixel size, is restricted in turn to the conventional Bayer matrix RGB bands. Despite this spectral limitation, satellite data are the primary source of information about urban wasted light at planetary scale (Cinzano et al., 2000, 2001; Cinzano and Elvidge, 2004; Sánchez de Miguel et al., 2014), correlate well with on-site flux measurements, and are useful tools for monitoring changes in upward light emissions after remodeling urban lighting systems (Estrada-García et al., 2015). The number of spaceborne

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instruments monitoring the city lights has been, however, comparatively very small until now (Belward and Skøien, 2015). Given the useful information they may provide and the relevance of the study of the anthropogenic emissions of light it is highly desirable that new satellite programs, ideally with nighttime multispectral capabilities, be planned in the near future.

Considerably better spatial and spectral resolution can be achieved with airborne hyperspectral imaging spectrometers, at the expense of a smaller area coverage. Hyperspectral imaging, that has found many applications in Earth imagery (see, e.g., Aasen et al., 2015; Clark and Kilham, 2016) including urban areas (Demarchi et al., 2014; Kotthaus et al., 2014), has also been successfully applied to the study of nighttime artificial lights (Barducci et al., 2003a, 2003b, 2006; Kruse and Elvidge, 2011). Airborne hyperspectral measurements combined with photogrammetric imagery allow to obtain reliable estimates of the upward luminance from urban areas with spatial resolutions well below one meter, as we have shown in previous works (Pipia et al., 2014; Corbera et al., 2015).

The overall radiant flux emitted towards the upper hemisphere by urban areas is a measure of the degree of lighting energy waste and is the leading cause of increased skyglow. This flux, however, is only part of the whole light pollution picture. Several detrimental effects of light pollution are essentially ground-level phenomena. They include, among others, light intrusion, disability and discomfort glare, light clutter, and the diverse photobiological effects of light at night. To evaluate the severity of these effects one needs to know the spectral radiance of the urban nightscape, as seen from the city dwellers standpoint. This radiance distribution allows the assessment of glare and light cluttering. It is also instrumental for computing the spectral irradiance in a plane tangent to the human corneal vertex for arbitrary gaze directions, which is the primary input for evaluating the physiological effects of light at night by means of suitable phototransduction models (CIE, 2015; Rea et al., 2005, 2010, 2012). The vertical irradiance on window panes allows, in turn, to quantify the severity of light trespass effects.

As in other areas of remote sensing (Chen et al., 2016), a comprehensive assessment of the overall levels of light pollution can only be achieved if the airborne and satellite data are complemented with ground based measurements acquired from within the town. In this work we describe the adaptation and operation of a hyperspectral imaging sensor routinely used for airborne surveys to acquire these additional datasets from the city streets. Hyperspectral light pollution measurements require dealing with spatially uneven, high dynamic range radiance distributions, and keeping the noise propagation within admissible levels. In Section 2 we describe the hyperspectral measurement system. The data reduction process implemented to get the desired magnitudes is summarized in Section 3. The results of a proof-of-concept measurement campaign carried out in the city of Barcelona are reported in Section 4. Discussion and conclusions are finally drawn in Sections 5 and 6, respectively.

2. Materials

2.1. Site selection

The field campaign was carried out at the city of Barcelona (3 million inh.), capital of Catalonia, in the period around the new Moon in February 19th to 20th, 2015. Its public outdoor lighting is mainly based on high pressure sodium vapor and metal halide lamps, with an increasing presence of phosphor-coated white Light Emitting Diode (LED) streetlights and self-luminous billboards. Several downtown areas were selected for measurements, including Plaça d'Espanya (site 1) and Jardinets de Gràcia (site 2), shown in Fig. 1, because they are zones presenting a high density of pedestrian traffic, main street intersections, and a representative sample of the lighting technologies used in the city.

2.2. Hyperspectral camera and mount

Hyperspectral data cubes were acquired with an AISA Eagle II sensor assembled on a HEQ5-Pro microprocessor-controlled astronomic equatorial mount. The mount declination axis was pointed vertically, so that the rotation around this axis allowed the camera to work in an azimuthal push-broom configuration. A lens of $f = 18.5$ mm imaged the urban nightscape onto the camera sensor, providing a vertical field of view of 37.7°. The 1024 native spatial pixels acquired in each of the spectral bands were binned 2×, giving an effective instantaneous field of view (*iFOV*) in the vertical direction of 4.4 min of arc. A total of 6990 azimuthal samples were acquired in each complete rotation of the mount, providing an horizontal *iFOV* of 3.1 min of arc. A spectral binning 4× provided 128 equally-distributed spectral channels from 390 nm to 1000 nm with 4.8 nm resolution.

Typical exposure times lie in the range 18–164 ms. The exposure times were chosen to fulfill geometric as well as radiometric criteria. From a geometric standpoint the exposure times were selected among those that provided an horizontal iFOV of the same order of magnitude than the vertical iFOV of the sensor, in order to avoid too large differences, and to obtain pixels as close to square as possible. Notice that the horizontal iFOV depends on the mount rotation speed and the sensor integration time, and that the available rotation speeds were limited to the discrete set of values provided by the commercial mount. The radiometric criterium is related to getting the optimal exposure of the scene, that is, trying to get the minimum number of saturated pixels and the maximum signal in dark areas. The flicker frequency of the sources shall also be taken into account: most urban light sources flicker at twice the AC mains frequency (50 Hz in Barcelona), with a modulation amplitude that may take a broad range of values, depending on the lamp technology, and may in many cases be significant. If exposure times are smaller than the flicker period (10 ms) some bias may appear in the detected radiance of individual sources. The influence of the flicker in the aggregate radiometric balance of the whole urban scene is attenuated due to the fact that urban light sources are often alternated in a 3-phase electrical system scheme. In our case the exposure times were always above this basic period, and close to integer multiples of it. The optimum settings to be used in each urban site strongly depended on the particular features of the illuminated nightscape, and were determined on a case-by-case basis by means of on-field analysis of trial scans. Raw images were stored with 12-bit effective depth for subsequent post processing. A typical pseudo-RGB panoramic image of the Jardinets de Gràcia site is displayed in Fig. 2.

3. Methods

In this section it is described on the one hand the theoretical frame of the work, including the products derived from the hyperspectral images, and, on the other hand, some image processing methods to deal with several image artifacts inherent to night images.

3.1. Output products

The spectral radiance of the nocturnal environment is the primary input for computing a set of specific magnitudes relevant for light pollution studies. Radiometric and photometric magnitudes can be easily computed from it. For instance, from the basic