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Quantifying light pollution

P. Cinzano [a], F. Falchi [a,b,*]

[a] Istituto di Scienza e Tecnologia dell'Inquinamento Luminoso (ISTIL), Via Roma 13, I-36016 Thiene, Italy
[b] CieloBuio, Coordinamento per la protezione del cielo notturno, Osservatorio Astronomico "G.V. Schiaparelli", Via A. Del Sarto 3, 21100 Varese, Italy

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ABSTRACT

In this paper we review new available indicators useful to quantify and monitor light pollution, defined as the alteration of the natural quantity of light in the night environment due to introduction of manmade light. With the introduction of recent radiative transfer methods for the computation of light pollution propagation, several new indicators become available. These indicators represent a primary step in light pollution quantification, beyond the bare evaluation of the night sky brightness, which is an observational effect integrated along the line of sight and thus lacking the three-dimensional information.

1. Introduction

Light pollution is not perceived as an issue for astronomy only anymore. In the last few years it has been recognised as a serious pollution problem, with negative consequences on environment (e.g. in [35,38,39,41]) and human health. Increasing epidemiological and [20] physiological evidences link light pollution and artificial light at night to several diseases such as sleep deprivation and disorders, diabetes, obesity and cancer (e.g. in [21,34,45]). This drives a growing interest on this issue.

At the same time, many international organisations and institutions are working to preserve humanity's capability to perceive the universe beyond the Earth (e.g. [13,40], see also the 2007 Starlight Declaration promoted by UNESCO, UN-World Tourism Organization, International Astronomical Union, Instituto de Astrofisica de Canarias and supported by several International Conventions like Ramsar, CBD, CMS, WHC).

The growing interest about light pollution requires methods for quantifying it and its effects.

In 1986 Roy Garstang introduced the modelling technique developed in the following years [22–30,32]. In 1998 Falchi and Cinzano for the first time used DMSP satellite data to compute maps of artificial and total sky brightness in large areas [17,19]. In the next years, using the Garstang modelling technique, Cinzano et al. [4,5,9–11] presented methods to map across large territories the artificial night sky brightness, the naked eye and telescopic limiting magnitude in any chosen direction of the sky, and to compute the distribution of the night sky brightness and the limiting magnitude over the sky hemisphere at any given site. The computations are based on the upward light emission radiance calibrated DMSP-OLS 30"x30" data [16] and the elevation from the GTOPO30 digital elevation map (Gesch et al., 1999) [33].

Their technique allows to generate a number of products and indicators:

1. Upward flux
2. Artificial night sky brightness at sea level

* Corresponding author at: Istituto di Scienza e Tecnologia dell'Inquinamento Luminoso (ISTIL), Via Roma 13, I-36016 Thiene, Italy. Tel.: +39 03487622936.
E-mail addresses: falchi@lightpollution.it, fabio_falchi@yahoo.it (F. Falchi).

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3. Total night sky brightness (accounting for elevation)
4. Stellar visibility (limiting magnitude)
5. Loss of stellar visibility (loss of limiting magnitude)
6. Statistical indicators like population-level indicators and area-level indicators (e.g. the fraction of population or the fraction of territory lying under a sky of given luminosity).

However the study of environmental and health consequences of light pollution requires the development of indicators that go beyond the traditional astronomical ones, in order to add to the monitoring of the artificial night sky brightness a specific quantification of the light pollution inside the atmosphere and on the ground surface.

In this paper we review indicators of light pollution and products available with recent observational and modelling techniques. In particular, we review the new indicators introduced by Cinzano and Falchi [8]. Some of them allow to analyse light pollution from the atmospheric content of pollutants point of view, like any other atmospheric pollution. In this case the pollutant is the manmade light in place of particulate or chemicals pollutants. This is a fundamental revision of the quantification of light pollution, so far based on the effects perceived by a subject (which could be an observer of starry sky as well as another living being like a sea turtle, a migrating moth or plankton on sea surface). These indicators allow to agree with the standard definition of “pollution” as “the introduction of contaminants into the natural environment that cause adverse changes”.

2. Indicators and products

Cinzano and Falchi [8] extended the seminal works of Garstang by providing a more general numerical solution for the radiative transfer problem applied to the propagation of light pollution in the atmosphere, which they called Extended Garstang Models (EGM). They retained the basic approach of the Garstang models of computing the irradiance on each infinitesimal volume of atmosphere produced by the sources, including now secondary sources, and accounting for the extinction along the path. EGM take advantage of a more detailed computation of radiative transfer, Mie and Rayleigh scattering, and line and continuous gas absorption using different atmospheric and surface models. Cinzano and Falchi [8] also presented the LPTRAN software package (which stands for Light Pollution radiative TRANsfer), an application of EGM to DMSP-OLS satellite measurements of artificial light emissions and to GTOPO30 (Global 30 Arcsecond) digital elevation data. LPTRAN provides an up-to-date method to predict the distribution of artificial brightness in the night sky at any site in the World at any visible wavelength for a broad range of atmospheric conditions and the artificial radiation density in the atmosphere across the territory. It nonetheless confirms the efficacy of the traditional Garstang models for a normally clean and transparent atmosphere. EGM account for (i) multiple scattering, (ii) 250 nm to near IR wavelength range, (iii) curvature and screening effects of Earth, (iv) elevation of both sites and sources, (v) custom setup of the atmosphere (including thermal inversion layers, mix of different boundary layer aerosols and tropospheric aerosols, up to five aerosol layers in upper atmosphere including fresh and aged volcanic dust and meteoric dust), (vi) scattering phase function changes with elevation, (vii) continuum and line gas absorption, including ozone, (viii) zero to five cloud layers, (ix) wavelength dependant bidirectional reflectance of the ground surface (e.g. snow) from NASA/MODIS satellites or custom data, (x) geographically variable upward light emission function given as a three-parameter function or a Legendre polynomial series. A more general solution also allows to account for (xi) mountain screening, (xii) geographical gradients of atmospheric conditions (e.g. localised clouds), (xiii) geographic distribution of different ground surfaces. To date, the software package LPTRAN is state-of-the-art in computing artificial night sky brightness and in quantifying light pollution.

EGM allow to compute classical indicators in a more detailed and sophisticated way. Moreover they allow to introduce more detailed indicators of light pollution. The ability of LPTRAN to collect radiation density and scattered light flux densities data on a 3D grid permits to introduce a *tomography of light pollution*, similar to a sectional radiography; it became possible to select a narrow section of atmosphere over a strip of considered territory and examine how these quantities vary with elevation or along the strip.

In Section 2.2 we review all the available indicators, both new and classical. We do not deal with statistical indicators already described by Cinzano et al. [11].

2.1. Integrated quantities vs. direction dependent quantities

Light pollution is the alteration of the natural quantity of light in the night environment produced by the introduction of manmade light. Quantification of light pollution means quantification of this alteration. The effects of light pollution usually depend on the direction of the light. Light intensity, a quantity depending on the direction, is the correct parameter to evaluate the effects of artificial light emitted by a source, or scattered from a volume of atmosphere centred in (x,y,z). Quantities integrated on the sphere or on the upward and downward hemisphere miss this fundamental directional information, which cannot be discarded when the effects of light pollution propagation are to be evaluated. Consequently the basic information on the propagation of artificial light in the atmosphere is given by intensity per unit surface $I_\lambda(x,y,z,\theta,\phi)$ where x and y are coordinates on the Earth's surface, z is the elevation and θ and ϕ are angles defining the considered direction. Note that the spectral intensity I_λ is given here for generality, but normally the correspondent quantity I, integrated over a given band, is used. The luminance in photopic or scotopic bands or the brightness in astronomical photometrical bands can be obtained with good approximation from the spectral radiance at the effective wavelength or, with more accuracy, by integrating the spectral radiance along the wavelength with the passband as weight.