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# Quantifying light pollution

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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

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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 $\theta$ and $\phi$ are angles defining the considered direction. Note that the spectral intensity $I_\lambda$ 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.

Integrated quantities become useful when the atmosphere is considered as a part of the environment affected by light pollution and not only as a medium of propagation. Integrated indicators of the alteration of the atmosphere summarise what would otherwise be too detailed information.

### 2.2. 2D indicators

*Bidimensional indicators* are usually presented as maps across the territory. If the indicator depends on the direction of observation, it can be presented as (i) maps across the territory of the quantity in a given direction of sky (e.g. zenith) or (ii) maps of the quantity across the sky in an individual site. The latter can be polar maps, Cartesian maps or hypermaps where the third coordinate is the atmospheric content Cinzano and Elvidge [6].

These indicators are:

(i) The *upward light flux* gives the manmade light flux emitted into the atmosphere. Sources are usually, but not exclusively, nighttime lighting installations. This indicator can be obtained from satellite data, by the DMSP Operational Linescan System since the ‘60 of the last century and by VIIRS (Visible Infrared Imaging Radiometer Suite) on Suomi satellite launched in 2011. Assumptions on the angular distribution of light emission, called upward light emission function, should be made to obtain the total upward flux from radiance measurements by satellites [3]. For discussion and measurements in retrieving upward emission function from satellite data see [9,12]. Careful attention should be given to the intercalibration issues of different DMSP satellites [12,43]. Secondary products such as variations/growth/decrease of upward flux can be obtained. Typical units are lm for light flux in CIE photopic or scotopic bands or ph $s^{-1}$ in other photometric bands. Flux is given “per land area covered by a pixel” in maps.

(ii) The *artificial night sky brightness* (*or radiance or luminance*) indicates the integral of artificial light scattered along an observer's line of sight. It has important effects on the perceived luminosity of the sky, on the star visibility, and consequently on the perception of the universe by humanity, on the darkness (or lack of it) of the environment; and is usually computed *at sea level* or *at ground level*. The night sky brightness perceived by an observer on the Earth surface in $(x, y, z)$ by looking in the direction of zenith angle and azimuth $\theta, \phi$ is simply $I_\lambda(x, y, z, \theta, \phi)$. It should be obtained integrating the light emission of each volume of the atmosphere along the line of sight, accounting for radiative transfer along the light path. Traditionally the night sky brightness is computed at zenith. When computing the night sky brightness in each direction $\theta, \phi$ over the upper hemisphere, several additional indicators become available, such as average night sky brightness, and maximum night sky brightness (e.g. in [8,14]).
We follow the traditional use in astronomy, by calling “night sky brightness” the flux of “anything” coming from the night sky per unit surface per unit solid angle, independent of the considered constituents (e.g. energy, light, photons, etc.) and independent from the quantity effectively measured (e.g. radiance, photon radiance, luminance, astronomical brightness, etc.), from its expression in a linear or logarithmic scale and from its units. Typical units are W $m^{-2}$ $sr^{-1}$ for energetic radiance, ph $s^{-1}$ $m^{-2}$ $sr^{-1}$ for photon radiance, cd $m^{-2}$ for luminance in CIE photopic or scotopic bands, mag $arcsec^{-2}$ in the selected astronomical photometric band for astronomical brightness in logarithmic scale, S10 units for astronomical brightness in linear scale in visual photometric band, etc. A very useful way to quantify light pollution is in relative term, by comparing the artificial quantity with the natural one. So that the artificial night sky brightness of a site can be expressed as the ratio between the artificial part and the corresponding natural pristine condition (e.g. [11,17,36]).

(iii) The *total night sky brightness* shows the ‘quality’ of the night sky in the territory as perceived by an observer, including the natural components of the night sky brightness. With *total* night sky brightness we mean the sum of the natural and the artificial components of it. Usually it is computed at zenith, accounting for the elevation. In smaller-size maps screening by mountains and terrain elevation can be taken into account [10]. The elevation, obtained from a digital elevation map (GTOPO30), influences the natural sky brightness, the artificial sky brightness and the stellar extinction. The natural sky brightness depends on the chosen direction of view and on the altitude and can be obtained following Garstang (1989) [25] for the airglow part. A detailed model of natural night sky brightness was given by Duriscoe [14]. The mountain screening can be accounted by evaluating the elevation of each pixel along the line which connect each site with each source and then computing the maximum screening angle that gives the shielded fraction of the line of sight. Units are the same as described above for the artificial night sky brightness.

(iv) The naked eye *star visibility* (limiting magnitude) shows the magnitude of the faintest visible star, i.e. the capability of the population to see stars. Generally it is computed at zenith, accounting for (a) the extinction of star light in the atmosphere from the top of the atmosphere to the observer and (b) the eye ability in detecting point sources against a light background (i.e. the polluted sky). This quantity is unsuitable to evaluate the light pollution of the atmosphere because of the confusing effects of elevation and extinction: having a similar limiting magnitude on a mountain and in the open ocean meaning that the mountain' sky is so polluted that the stellar visibility there is comparable to that from sea level. As Blackwell [1] and many other authors showed, the relation between limiting magnitude and sky brightness is not linear and, moreover, the detection of a faint star is a statistical concept. Several factors affect our eyes ([31]; Schaefer, 1990 [42]), like the individual eye acuity, the pupil size, the individual experience that makes the observer confident of detecting at a lower probability level different from a novice, the length of the observation, fatigue, and the altitude (at higher altitude less oxygen lower the eye's sensitivity). So we can predict the star visibility by only considering an average observer in spite of accounting for many details (e.g. observer pupil diameter depending on the age; Stiles–Crawford effect (a decrease of the efficiency in detecting photons with the distance from the centre of the pupil)); colour differences between the laboratory sources and the observed star; colour differences between the laboratory sources and the night sky; differences between the night vision curve and the V band in computing the stellar extinction. Unit is typically magnitude in V band or in visual band.

(v) The *loss of star visibility* (loss of limiting magnitude) shows the loss of the capability of the population to see the stars, due to an increase in background luminosity. It is the difference between the star visibility and the same quantity evaluated assuming a perfectly pristine unpolluted sky. Contrary to the previous and the next indicators, in this case the effects of light pollution are less ambiguous. These maps are less useful to find the best observing sites than the previous or the next indicator. The loss of naked eye limiting magnitudes are usually computed for observers of average experience and capability, aged 40 years, with eyes adapted to the dark, and observing with both eyes toward the zenith.

(vi) The *number of visible stars* in a clear night is a new indicator recently introduced for popularisation purposes (Cinzano, in preparation), because general public understand it better than star visibility. Its computation is not trivial. In fact there is no biunivocal relation between the number of visible stars and the zenith limiting magnitude: (a) V mag vs. star number is not exactly exponential and not well defined in catalogues, (b) sky brightness changes with the direction of observation, requiring integration over the visible hemisphere or modelling, (c) stellar extinction and stars apparent magnitude change with elevation. The number is estimated for observers of average visual astronomy experience and capability, aged 40 years, with eyes fully adapted to the dark, observing with both eyes the upward hemisphere and counting all the surely seen stars (detection probability 98%). Maps of the loss of the number of visible stars are obtained by the difference between a map of the number of visible stars and a map of the same quantity evaluated assuming no light pollution. Like the maps of loss of star visibility, these maps show the effects of light pollution but are less useful to evaluate the capability to see the stars (best observing sites) than the maps of the number of visible stars.

(vii) The *sky irradiance or the sky illuminance on the Earth surface*, is an indicator that gives information not only on the luminosity of the ground surface but also on the luminosity of the night environment as perceived by flora and fauna, humans included (of course where light pollution due to direct irradiance by nearby lighting installations is negligible); the total horizontal irradiance $i_{\lambda,g}$ on the Earth surface is

$$i_{\lambda,g}(x,y)=\int_0^{2\pi}\int_0^{\pi/2} I_\lambda(x,y,z_g,\theta,\phi)\ \cos\ \theta\ \sin\ \theta\, d\theta\, d\phi. \tag{1}$$

Several other indicators can be computed from $I_\lambda(x,y,z,\theta,\phi)$ by integration over the entire hemisphere: horizontal illuminance [8], average and maximum vertical illuminance [14], scalar illuminance [14]. Depending on the site, these indicators should also take into account the contribution from the lower hemisphere due to reflection from the ground and the contribution of direct sources of pollution (e.g. a site on a mountain overlooking a valley with light sources).

All these integrated and 'maximum' indicators can be very helpful in quantifying light pollution at a site with a 'single number' that immediately shows the contamination of the site. Sites that have negligible contamination at zenith may have substantial contamination at lower altitude that these indicators show easily.

Some of these indicators can also be obtained from direct measurements. The upward flux is usually obtained from satellite radiance measurements, night sky brightness from astronomical measurements (e.g. [7,15,18]), and limiting magnitude from observational campaigns (e.g. [10,11]). The illuminance on the Earth's surface due to the sky can be directly measured with an high sensitivity lux-metre/irradiance-metre or indirectly by properly integrating the measurements of night sky brightness on the upper hemisphere, after conversion from logarithmic to linear scale and accounting for the cosine projection effect on the horizontal plane. Typical units are W m$^{-2}$ for energetic irradiance, ph s$^{-1}$ m$^{-2}$ for photon irradiance in the chosen photometric band, and lm m$^{-2}$ (i.e. lx) for illuminance in CIE photopic or scotopic bands.

### 2.3. 3D indicators

#### 2.3.1. 3D indicators, can be presented as a 3D-array

(i) The *radiation density* in the atmosphere is the number of photons in unit time (or the energy, or the light) per atmosphere's unit volume in the course of transit, in the neighbourhood of the points ($x$, $y$, $z$). This is the best indicator for atmospheric light pollution because it can quantify how much content of natural light of the atmosphere is altered by the introduction of artificial light. Radiation density is also useful in predicting and quantifying the effects of urban lighting in the atmosphere's photochemistry [44]. What we call *radiation density* in this paper can be expressed more generally as (i) radiation energy density (energy per unit volume in J m$^{-3}$) or (ii) photon density (photons per unit volume in ph m$^{-3}$). Moreover, in CIE photopic and scotopic bands, the radiation density of light can be expressed as luminous energy density (luminous energy per unit volume in Tb m$^{-3}$, where talbot (Tb = lumen × second) is the unit of luminous energy). We use Tb as the talbot symbol to avoid any confusion with the Tesla unit (T), the terabyte (TB) and terabit (Tbit).

Usually in air and water chemical pollution the flux of the source can be small, but it accumulates in the medium, and even after the polluting source is removed, the density pollutant or contaminant decays slowly. In light pollution this accumulation and decay practically do not exist and switching off the light sources results in abrupt decay of the photon density. In other words, in classic air pollution the flux of the sources and the density of the pollutant in the medium are not directly correlated as in light pollution. This does not mean that light pollution, having no accumulation in the atmosphere, can be eliminated easily by switching off light sources, unless in case of catastrophic events. The migration toward better and less pollutant technologies and practices is very slow (e.g. fully shielding of fixtures instead of more polluting sources) and sometimes 'reversed', increasing light pollution (e.g. the migration toward high blue content light sources such as white LEDs). Moreover, the almost continuous increase of the installed light flux is an anomaly in the pollution control strategies that usually require a decrease of the contaminants over the years.

LPTRAN allows to obtain the artificial radiation density, which is the manmade fraction of the total radiation density. To quantify the alteration of the natural light content in each volume of the atmosphere due to the introduction of artificial light we can consider the atmosphere (and the environment) polluted when the artificial radiation density is greater than 10% of the natural one, as for the night sky brightness. The natural radiation density is approximately of the order of $2.6\times10^{-3}$ Tb km$^{-3}$ (i.e. lm s km$^{-3}$) in soil. Reader should be aware that an artificial radiation density in the atmosphere lower than 10% of the natural one can be considered an indication that the alteration of the atmospheric content of light is negligible but it does not automatically mean that the night sky can be considered unpolluted. The artificial night sky brightness is an effect of light pollution which depends on the direction of the polluting light and not only on its flux.

(ii) The radiation density can be split in *upward and downward radiation densities*, useful to quantify the light directed back to Earth surface (approximately: due to the curvature of the Earth, not all the downward light goes on the ground) and the light directed to outer space; the downward radiation density $u_{\lambda,d}(x,y,z)$ is

$$u_{\lambda,d}(x,y,z)=\frac{1}{c}\int_0^{2\pi}\int_{\pi/2}^{\pi} I_\lambda(x,y,z,\theta,\phi)\sin\theta\, d\theta\, d\phi. \quad (2)$$

In fact, if $i=dE/dSdt$ is the energy flux per unit surface per unit time at $(x,y,z)$, the radiation density is expressed as energy per unit volume is $dE/dV=(dE/dSdt)(dt/dr)=i/c$ where $c=dr/dt$ is the velocity of the light (see e.g. [2] for a more detailed derivation). The upward radiation density is obtained integrating for $\theta$ between 0 and $\pi/2$.

(iii) The *radiation density due to direct illumination* by the sources is the direct light from polluting sources travelling through a unit volume of atmosphere. It quantifies how much volume of atmosphere is directly "lighted" by artificial light sources.

(iv) The *upward and downward scattered flux densities* are the flux density of the scattered radiation; the downward one, in particular, quantifies the importance of each unit volume of the atmosphere in $(x,y,z)$ as a secondary source of light pollution. The density $s_{\lambda,d}(x,y,z)$ of the flux scattered downward by a unit volume of atmosphere centred in $(x,y,z)$ is

$$s_{\lambda,d}(x,y,z)=\frac{1}{c}\int_0^{2\pi}\int_{\pi/2}^{\pi} F_\lambda(x,y,z,\theta,\phi)\sin\ \theta\, d\theta\, d\phi. \quad (3)$$

where $F$ is the light flux scattered in the direction $(\theta,\phi)$ by a unit volume of atmosphere in $(x,y,z)$ and can be obtained from LPTRAN. The upward scattered flux is obtained integrating for $\theta$ between 0 and $\pi/2$. These densities are not density of radiation (e.g. number of photons per unit volume) but density of flux (e.g. number of photons per unit time per unit volume). Units: density of flux in ph s$^{-1}$ m$^{-3}$.

Even if these new 3D indicators could appear as obtainable only from detailed modelling of the atmosphere, some of them can be measured directly. The upward and downward radiation density in the atmosphere are directly measurable with an hemispherical illuminance/radiance metre oriented with its axis respectively upward or downward. Measurements can be carried out from a balloon, an airplane (e.g. [37]), a drone or a mountain. Cinzano and Falchi (in preparation) are planning a balloon experiment called LIGHTRAD.

We stress once again that these integrated quantities are useful as generic indicators of the alteration of the atmosphere. The effects of atmosphere as a secondary source of light pollution should be evaluated based on the intensity of light in each direction at each volume and not based on integrated quantities like fluxes, which do not account for the direction of light. Just like light pollution from lighting installations should be evaluated based on the intensity of light in each direction and not based on integrated quantities like the total upward flux.

To quantify the alteration of the natural light flux in each volume of the atmosphere due to the introduction of artificial light we can consider the atmosphere (and the environment) polluted when the artificial radiation density is greater than 10% of the natural one, as for the night sky brightness. We underline here that having an artificial zenith sky brightness lower than 10% of the natural one does not mean that the sky can be considered unpolluted. At lower elevation the artificial brightness will be typically much higher. For this reason additional indicators such as average hemispheric luminance, maximum luminance, average and maximum vertical illuminance become very useful.

## 3. Application

As an example of *tomography of light pollution*, Cinzano and Falchi [8] presented a vertical section of the atmosphere above the Veneto plane along a line at constant latitude 46°26′ North showing the downward artificial radiation density in the atmosphere. Using the same atmospheric condition we computed both the upward

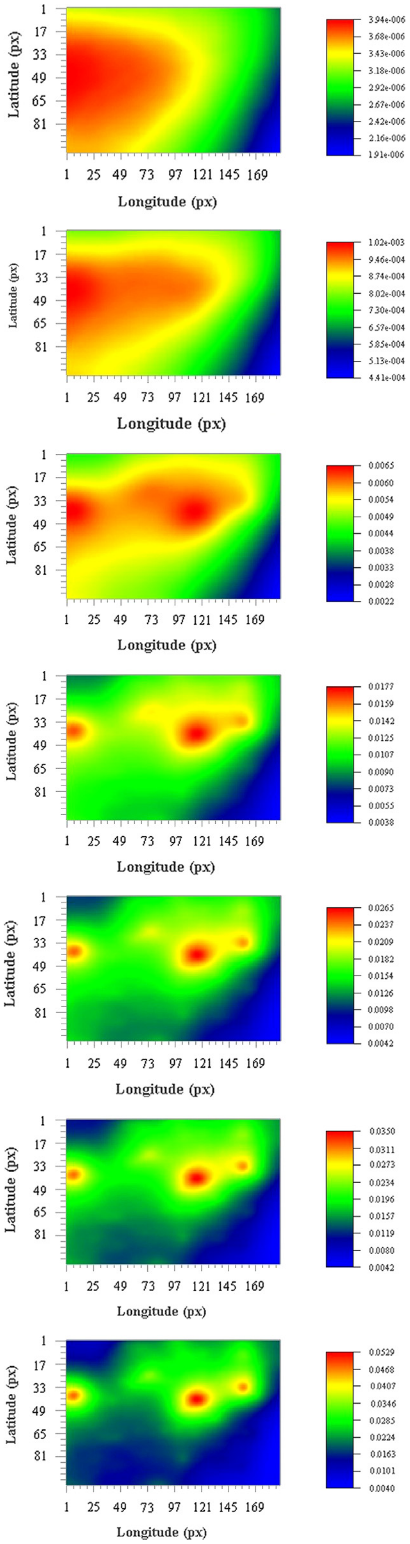


**Fig. 1.** Downward artificial radiation density in Tb km$^{-3}$ (i.e. lm s km$^{-3}$) along some horizontal sections of the atmosphere taken at different elevations above Veneto plane, Italy, as a function of the position in pixels. From top to bottom, sections shows the average density inside volumes of atmosphere centered respectively at elevations of 47.5 km, 20.5 km, 10.5 km, 4.5 km, 2.5 km, 1.5 km, and 0.5 km. The natural radiation density is approximately of the order of $2.6 \times 10^{-3}$ Tb km$^{-3}$.

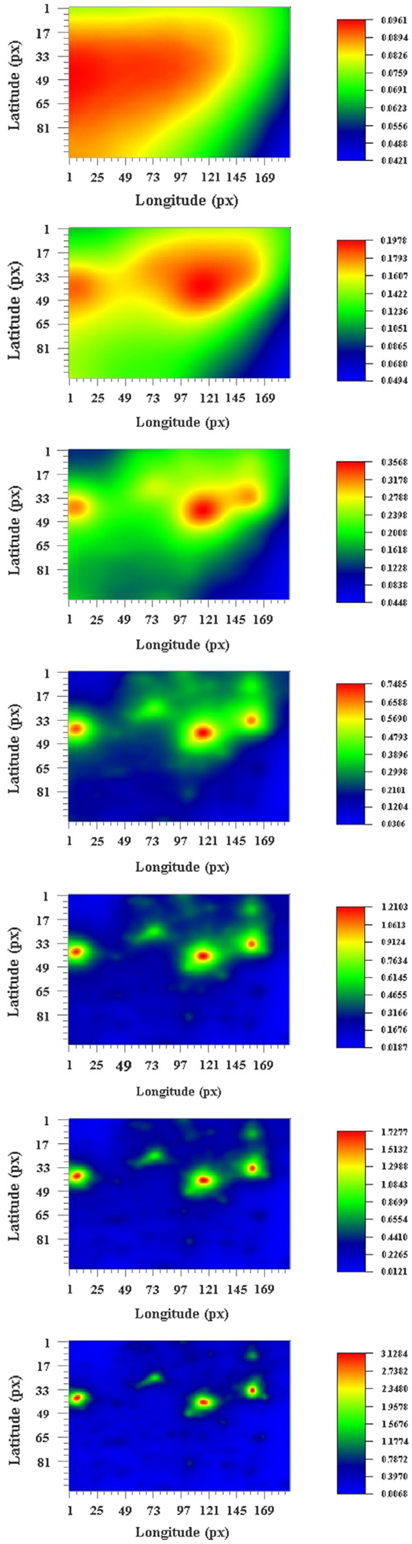


**Fig. 2.** Upward artificial radiation density in Tb km$^{-3}$ (i.e. lm s km$^{-3}$) along some horizontal sections of the atmosphere taken at different elevations above Veneto plane, Italy, as a function of the position in pixels. From top to bottom, sections shows the average density inside volumes of atmosphere centred respectively at elevations of 47.5 km, 20.5 km, 10.5 km, 4.5 km, 2.5 km, 1.5 km, and 0.5 km. The natural radiation density is approximately of the order of $2.6 \times 10^{-3}$ Tb km$^{-3}$.

and downward artificial radiation density in several horizontal sections at different altitudes over the same region. The total radiation density is the sum of the two quantities. Computation was made with LPTRAN in the photometric astronomical V band for a clean atmosphere with an aerosol clarity coefficient $K=1$ [23]. This corresponds to a vertical extinction of 0.33 magnitudes in the V band, a horizontal visibility $\Delta x=26$ km and an optical depth $\tau=0.3$ (as in [9,11]). Input DMSP-OLS radiance data, GTOPO30 DEM data and calibration were the same as Cinzano et al. [11] and Cinzano and Elvidge [6]. The atmospherical sections were taken above a polluted area of the Veneto plane, Italy, including from West to East, the cities of Verona, Vicenza, Padova and Venezia.

We present in Figs. 1 and 2 respectively the downward and upward artificial radiation density in Tb $\text{km}^{-3}$ (i.e. lm s $\text{km}^{-3}$) along some horizontal sections of the atmosphere taken at different elevations above the same area. Sections shows the average density inside a volume of atmosphere centred respectively at elevations of 47.5 km, 20.5 km, 10.5 km, 4.5 km, 2.5 km, 1.5 km, 0.5 km. The colour scale changes for each section due to the variability of the range from section to section which prevent the use of the same colour scale for the entire set. We refer the reader to Cinzano and Falchi's paper [8] for details. Readers should be aware that the volume indexes in Fig. 6 are reversed with respect to volume numbers in Table 1 of the same paper.

## 4. Conclusions

Artificial light propagates in the atmosphere altering the natural quantity of light in the involved medium, just like other physical or chemical pollutants alter its content. So light pollution it is not a bare alteration of the background for an observer of the night sky but a true atmospherical and environmental pollution. While the most used and known indicator of light pollution is the night sky brightness, here we reviewed a number of indicators, recently introduced by Cinzano and Falchi [8], that allowed us to quantify the alteration of the atmosphere more properly. These indicators allow to enhance light pollution mapping from the old 2D grid (geographical position or position on the celestial sphere) to a 3D grid (geographical position and elevation). The new LPTRAN modelling technique allows to compute these new indicators, some of which are also experimentally measurable, giving the researcher the capability to carry out a tomography of light pollution in the atmosphere, similar to a sectional radiography. A number of refinements can still be done in future years, in particular the availability of spectra or multiple bands of the artificial light emissions taken from satellites will allow to update these indicators to spectral quantities or to non-standard photometric bands which could be required for specific studies.

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## References

[1] Blackwell HR. J Opt Soc Am 1946;36(11):624–32.
[2] Chandrasekhar S. Radiative transfer. Oxford: Clarendon Press; 1950.
[3] Cinzano P. Mem Soc Astron Italy 2000;71:93–112.
[4] Cinzano P, Elvidge CD. In: Schwarz HE, editor. Light pollution: the global view. Dordrecht: Kluwer; 2003. p. 29.
[5] Cinzano P, Elvidge CD. Mem Soc Astron Italy 2003;74:456.
[6] Cinzano P, Elvidge CD. Mon Not R Astron Soc 2004;353:1107.
[7] Cinzano P, Falchi F. A portable wide-field instrument for mapping night sky brightness automatically. Mem SAIt 2003;74:458–9.
[8] Cinzano P, Falchi F. Mon Not R Astron Soc 2012;427:3337–57, http://dx.doi.org/10.1111/j.1365-2966.2012.21884.x.
[9] Cinzano P, Falchi F, Elvidge CD, Baugh KE. Mon Not R Astron Soc 2000;318:641.
[10] Cinzano P, Falchi F, Elvidge CD. Mon Not R Astron Soc 2001;323:34.
[11] Cinzano P, Falchi F, Elvidge CD. Mon Not R Astron Soc 2001;328:689.
[12] Cinzano P, Falchi F, Elvidge CD. Recent progresses on a second world atlas of the night-sky brightness, in starlight—a common. In: Heritage Cipriano, Marin, Jafari Jafar, editors. Starlight Initiative and Instituto de Astrofisica de Canarias Publishers; 2007. p. 385–400.
[13] Crawford DL. ASP Proceedings of IAU colloquium 112, Light pollution, radio interference and space debris. Conference series, vol. 17, Astron. Soc. Pac., San Francisco; 1991.
[14] Duriscoe DM. PASP 2013;125(933):1370–82.
[15] Duriscoe DM, Luginbuhl CB, Moore CA. PASP 2007;119:192.
[16] Elvidge CD, Baugh KE, Dietz JB, Bland T, Sutton PC, Kroehl HW. Remote Sens Environ 1999;68:77.
[17] Falchi F. [Master's thesis] Università di Milano; 1998.
[18] Falchi F. Mon Not R Astron Soc 2011;412:33.
[19] Falchi F, Cinzano P. Mem Soc Astron Italy 2000;71:139.
[20] Falchi F, Cinzano P, Elvidge CD, Keith D, Haim A. J Environ Manage 2011;92:2714.
[21] Fonken LK, Nelson RJ. Illuminating the deleterious effects of light at night. F1000 Med Rep 2011;3:18.
[22] Garstang RH. Observatory 1984;104:196.
[23] Garstang RH. PASP 1986;98:364.
[24] Garstang RH. In: Millis RL, Franz OG, Ables HD, Dahn CC, editors, Identification, optimization and protection of optical observatory sites. Flagstaff: Lowell Observatory; 1987. p. 199.
[25] Garstang RH. Observatory 1988;108:159.
[26] Garstang RH. PASP 1989;101:306.
[27] Garstang RH. Annu. Rev. Astron. Astrophys. 1989;27:19–40.
[28] Garstang RH. PASP 1991;103:1109.
[29] Garstang RH. In: Crawford DL, editor, ASP Conference Series, vol. 17, IAU colloquium 112, light pollution, radio interference and space debris. Astron Soc Pac. San Francisco; 1991. p. 56.
[30] Garstang RH. Observatory 1991;111:239.
[31] Garstang RH. Mem Soc Astron Italy 2000;71(1):71–81.
[32] Garstang R. Br Assoc Adv Sci 2001;33:786.
[33] Gesch DB, Verdin KL, Greenlee SK. EOS Trans. Amer. Geophys. Union 1999;80:69.
[34] Haim A, Portnov BA. Light pollution as a new risk factor for human breast and prostate cancers. Dordrecht: Springer Publishing; 978-94-007-6220-6.
[35] Hölker F, Wolter C, Perkin EK, Tockner K. Light pollution as a biodiversity threat. Trends Ecol Evol 2010;25(681–682):2.
[36] Hollan J. What is light pollution and how do we quantify it?; 2006 [retrieved 22.12.13] ⟨http://amper.ped.muni.cz/light/lp_what_is.pdf⟩.
[37] Kuechly HU, Kyba CCM, Ruhtz T, Lindemann C, Wolter C, Fischer J, et al. Remote Sens Environ 2012;126:39–50.
[38] Kyba CCM, Ruhtz T, Fischer J, Hölker F. Cloud coverage acts as an amplifier for ecological light pollution in urban ecosystems. PLoS ONE6 2011;3:e17307. http://dx.doi.org/10.1371/journal.pone.0017307.

[39] Longcore T, Rich C. Ecological light pollution. Front Ecol Environ 2004;2(4):191–8.
[40] Marin C, Jafari J, editors. Stalight A Common Heritage, Canary Islands, Spain: Starlight Initiative and Instituto de Astrofisica de Canarias; 2007.
[41] Navara KJ, Nelson RJ. The dark side of light at night: physiological, epidemiological, and ecological consequences. J Pineal Res 2007;43: 215–24.
[42] Schaefer BE, Feb. Telescopic Limiting Magnitude. PASP 1990:212–29.
[43] Small C, Elvidge CD. Mapping decadal change in anthropogenic night light. Proc Environ Sci 2011;7(2011):353–8.
[44] Stark H, Brown SS, Wong KW, Stutz J, Elvidge CD, Pollack IB, et al. City lights and urban air. Nat Geosci 2011;4:730–1. http://dx.doi.org/10.1038/ngeo1300.
[45] Stevens RG, Blask ED, Brainard CG, Hansen J, Lockley SW, et al. Meeting report: the role of environmental lighting and circadian disruption in cancer and other diseases. Environ Health Perspect 2007;1159:1357–62.