Nighttime monitoring of the aerosol content of the lower atmosphere by differential photometry of the anthropogenic skyglow

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ABSTRACT

Nighttime monitoring of the aerosol content of the lower atmosphere is a challenging task, because appropriate reference natural light sources are lacking. Here we show that the anthropogenic night sky brightness due to city lights can be successfully used for estimating the aerosol optical depth of arbitrarily thick atmospheric layers. This method requires measuring the zenith night sky brightness with two detectors located at the limiting layer altitudes. Combined with an estimate of the overall atmospheric optical depth (available from ground-based measurements or specific satellite products), the ratio of these radiances provides a direct estimate of the differential aerosol optical depth of the air column between these two altitudes. These measurements can be made with single-channel low-cost radiance detectors widely used by the light pollution research community.

Key words: light pollution – scattering – radiative transfer – atmospheric effects – instrumentation: photometers

1 INTRODUCTION

Monitoring the aerosol content of the lower atmosphere is relevant for characterizing the atmospheric boundary layer dynamics. Nighttime aerosol observations, however, are significantly more demanding than their daytime counterparts, specially if passive techniques (i.e. those based on light not emitted by the observer) are to be used. Whilst during daytime the Sun provides a reliable and radiometrically well characterized light source allowing for continuous aerosol monitoring (AERONET 2020), the night lacks such a natural lighting standard with the required attributes.

City lights offer an alternative source of photons to sample the nocturnal atmosphere. Artificial light emitted from urban and rural nuclei, roadway infrastructure, and diverse industrial, agricultural or extractive facilities, is a pervasive feature of the modern world. A non-negligible amount propagates toward the upper hemisphere, either directly or after being reflected on different natural and artificial surfaces. A fraction of this light leaves the upper atmosphere and can be analysed by spaceborne instruments. Other fraction propagates downward, being perceived by ground-based observers as light pollution in form of increased sky brightness (anthropogenic skyglow). Both light beams interact with the atmospheric constituents through spatially distributed processes of absorption and scattering, and contain information about their composition and volume distribution, predominately aerosols (Ścieżkor and Czaplicka 2020).

Remote sensing of city lights from low-Earth orbit has been recently proposed as a useful tool for atmospheric research. Direct line-of-sight radiometry of urban lights allows to determine, among other parameters, the aerosol optical depth (AOD) (Choo and Jeong 2016; Johnson et al. 2013; McHardy et al. 2015; Wang et al. 2016; Zhang et al. 2008, 2019). The halos of scattered light observed from space around ground light sources also provide interesting information. Sánchez de Miguel et al. (2020) have shown that their scattered upward radiance is correlated with the downward one, and hence with the light perceived by ground-based observers as anthropogenic skyglow, thus providing a feasible tool for wide-area light pollution monitoring. Analysing these halos, Kocifaj and Bará (2020) developed a method for estimating the number-size distribution of aerosol particles in the nocturnal air column from the angular distribution of the upward scattered light.

We describe here a new application, namely a practical approach for determining the difference in aerosol optical depth (ΔAOD) between two altitudes in the nocturnal...
air column, based on differential photometry of the artificial skylight. $\Delta AOD$ could be derived from ground $AOD$ if the aerosol scale height for the exponential atmosphere were known. However, the instantaneous aerosol scale height is generally unavailable for a specific site, and using mean values can result in considerable errors. The method here described allows estimating $\Delta AOD$ from measurements of the zenith sky brightness made at two different altitudes, in the vicinity of the urban centres, and having a good estimate of the total $AOD$. The ratio between these radiances provides a good estimate of the fraction of the total $AOD$ that is due to the aerosols in the layer between the two measuring heights. $\Delta AOD$ is important for characterizing the nocturnal contamination of the lower atmosphere, which is typically unknown because many detectors (like those at AERONET stations) are designed to monitor columnar aerosol optical properties (Kim et al. 2007) and primarily operate in daytime. This monitoring network has also taken advantage of moonlight (Berkoff et al. 2011), but these data are available at a few stations and are mostly limited to the nights near full moon. Since the data coverage is extremely uneven and sparse (we notice there is only one AERONET station in Slovakia), the use of this product is restricted to relatively few sites. The measurements required by our approach can be made with relatively low-cost instruments widely used by the light pollution research community (Hanel et al. 2018). We expect this method can contribute to increase the amount and the quality of aerosol data in the nocturnal atmosphere.

2 MODELING THE DEPENDENCE OF THE ZENITH SKY BRIGHNESS WITH ALTITUDE

The artificial night sky radiances are due to the backscattering of the city light emissions in the Earth atmosphere. In a random multiple scattering atmosphere the NSB can be obtained by solving the radiative transfer equation with adequate boundary conditions. However, for optically thin media with total optical depth not exceeding unity, the scattered light field may be advantageously decomposed into scattering modes, a procedure known as the method of successive orders. This approach is particularly useful when the first scattering mode dominates the remaining ones, as e.g. when the light beams travel short optical paths (Kocifaj 2018). This is the usual case when the NSB is observed close to an artificial light source. For example, in mountain regions under clear skies and $AOD$ below 0.3, the expected second-scattering radiances at the zenith ranges from 2% to 9% of the radiances of the single scattering component (based on own computations, not shown here). In these cases the NSB can be computed much faster using a single-scattering approximation than by superimposing many high-order modes (ibidem and in Aubé (2015)). We have shown in (Kocifaj 2018) that the first and higher scattering radiances components vary strongly with the atmospheric optical depth.

Let us recall that the aerosol optical depth ($AOD$) and the Rayleigh optical depth ($ROD$) are defined for a vertical beam path from a given altitude $h$ to the top of the atmosphere. $AOD$ or $ROD$ are the natural logarithms of the incident-to-transmitted radiant power for an aerosol or a molecular atmosphere, separately. The scattering phase function, in turn, characterizes the angular distribution of the radiance scattered by a small atmospheric volume. This is a wavelength-dependent function with a large anisotropy in turbid media with high concentration of aerosols of sizes comparable to (or larger than) the wavelength of light (Mishchenko 2009). The particles whose sizes and optical properties tend to differ from those of Rayleigh scatterers are often called Mie scatterers (although the conventional Mie theory is exclusively applicable to homogeneous spherical particles). Their shapes can be arbitrary and their sizes are too large for being approximated by a single pointlike dipole source. To compute their far-field scattered radiance each particle shall be replaced by large array of point dipoles. The superposition of all scattered waves, with different relative phases, tends to produce a complex scattering pattern. Hence the scattering phase function is expected to vary greatly with the microphysical properties of aerosols, specifically their sizes, shapes, and compositions, but also with the specific way in which the individual particles are distributed within the scattering volume.

Not all the above mentioned parameters have the same role in shaping the patterns of diffuse light at night. Some of them are particularly significant and should be determined with care, specially when they vary quickly in time. The spectral ground reflectance may be very different from one city to another and shows relevant seasonal trends (permanent snow cover, leaf litter...), but, excepting for transient episodes of rain or snow coating, it may be expected to be relatively constant at the city scale across any typical single night. The aerosol system, however, plays a key role. It is highly unstable and sensitive to meteorological conditions at the observing site, and often undergoes abrupt changes in short characteristic times, as e.g. with wind direction or passage of atmospheric fronts. The aerosol microphysics also changes with air humidity, local production, transport and chemical transformation of particles, and hence the scattering and absorption properties of aerosols tend to vary from day to day and even within a single day in any particular site. Moonlight may also influence the measurements significantly (Puschign et al. 2020; Cavazzani et al. 2020a,b) by reshaping the radiances patterns, therefore it is highly preferred to make the observations during moonless nights or when the Moon is low.

For many applications we are interested in monitoring the NSB changes in sites whose parameters are reasonably constant or have a well known and deterministic temporal variation. This applies notably to the emissions of the city lights: although the spatial distribution, composition, orientations and angular emission functions of individual light sources are generally unknown for a city, these factors are fairly constant or vary predictably across a single night (see, e.g. Dobler et al. (2015); Meier (2018); Bará et al. (2019a)). Among all site-specific parameters, we have found that the optical depth is the most relevant one when it comes to determining the artificial zenith radiances. We have performed a number of numerical experiments to select the variables most influential on the NSB changes recorded at two different altitudes. In spite of potential discrepancies between the theoretically assumed atmospheric profiles and the actual ones, we have found that the ratio of zenith radiances measured by a ground-based station and other located at an altitude $h$ above ground level is basically driven by the optical thickness of the lower atmospheric layer comprised.
between the two stations, $\Delta \tau_{0-h}$, and by the optical depth of the atmosphere above the highest one, $\tau_h$. Henceforth we will use the term $\Delta OD = \Delta AOD + \Delta ROD$, the differential optical depth, as an equivalent notation for $\Delta \tau_{0-h}$.

The ground-normalized zenith radiance, defined as the ratio of the zenith radiance at altitude $h$ ($I$) to its value at ground-level ($I_0$), is shown in Fig. 1 as a function of the optical depth of the lower atmospheric layer, $\Delta OD$. The calculations were made for a narrow spectral band centered at 530 nm (the average wavelength of the device spectral response) using the theoretical model published in (Kocifaj 2018). The results are given for a set of typical values of the ground level $AOD$, the columnar aerosol optical depth, a commonly available satellite product (Shahzad et al. 2018; Hasekamp et al. 2019; Chong et al. 2019). The numerical calculations have been made including five scattering orders, using the expressions (1,6,14-15) of the theoretical model described in (Kocifaj 2018). This number of scattering orders allow us obtaining reliable results even for atmospheres with high aerosol content, and hence large $AOD$ values. The results are shown as a function of $\Delta OD$ for $AOD$ ranging from 0 to 0.6. It can be seen in Fig. 1 that the differential optical depth $\Delta OD$ between both stations can be univocally determined for any $AOD$ value from the measured ground-normalized zenith radiance $I/I_0$. For instance, if both $I/I_0$ and $AOD$ are 0.4 then $\Delta OD \approx 0.15$, as indicated in the Figure.

3 AN APPROXIMATE FORMULA FOR THE GROUND-NORMALIZED ZENITH BRIGHTNESS

Air molecules and particles much smaller than the wavelength of light scatter in the Rayleigh regime, with a scattering efficiency inversely proportional to the fourth power of the wavelength, and a forward scattering lobe identical to the backward one. The scattering phase function is anisotropic for most kind of aerosols, and their wavelength dependence is smaller than for Rayleigh scatterers. Therefore, the largest differences in the underlying physics can be expected to occur when transitioning from an aerosol-free atmosphere to slightly turbid one. Assuming that the turbid atmosphere is lit from below by a huge amount of point light sources we have found, after lengthy mathematical derivations, that the ground-normalized zenith radiance near a city can be approximated by the formula:

$$\frac{I}{I_0} = \frac{\tau_0}{\tau_0 - \tau_h} e^{\tau_h} - e^{-\tau_h},$$

where $\tau_h$ is the atmospheric optical depth above the elevated station, and $\tau_0 = AOD + ROD$ is the corresponding value at ground level. The optical thickness of the lower atmospheric layer is $\tau_0 - \tau_h = \Delta \tau_{0-h} = \Delta OD = \Delta AOD + \Delta ROD$. Eq. 1 shows a progressively better coincidence with the exact theoretical predictions when the $AOD$ values increase. This is shown in Fig. 2, where the dashed lines correspond to Eq. 1, while the dots are the results of the numerical integration of the exact equations governing the artificial night sky radiance. The solid lines in this Figure correspond to the exponential functions that best fit the exact computational results (shown as dots as indicated above). Furthermore, assuming that the average $\Delta OD$ at the effective instrumental wavelengths decreases exponentially with the altitude, $\Delta OD \propto 0.118 e^{-h/8}$ ($h$ is in km), we found the following approximate expression for the ground-normalized zenith radiance:

$$\frac{I}{I_0} \approx e^{a h + b h},$$

where $a \equiv -1.64 \text{ km}^{-1}$ and $b \equiv -0.46 \text{ km}^{-1}$. In the formula for $ROD$ the coefficient 0.118 is the theoretical $ROD$ at sea level, while the value 8 in the exponent is the altitude (km) up to which a homogeneous molecular atmosphere would extend. Fig. 2 also shows that the ratio $I/I_0$ modelled from Eq. 1 tends to deviate significantly from the numerical exact values when the $AOD$ is approaching zero (i.e. approaching an aerosol-free, purely molecular atmosphere). In an aerosol-free atmosphere the average discrepancy between the numerical and the approximate values is 25%, reducing to only 7% for $AOD=0.2$, and just 2% for $AOD=0.4$. Let us finally note that $I/I_0$, as per Eq. 1, decreases proportionally to the square of $\tau_h$ as $h$ increases, since $I/I_0$ asymptotically approaches $2 e^{2\tau_h} \frac{1}{(1-e^{-\tau_h})}$. The formula is obtained from Eq. 1 by applying Taylor-series expansion to the exponential functions of $\tau_h$, assuming $\tau_h$ is a small value at elevated altitudes. In turn, $I/I_0 \to 1$ when $\tau_h \to \tau_0$, i.e. when the altitude $h$ of the elevated station approaches that of the base one.
4 EXPERIMENTAL RESULTS FROM A FIELD MEASUREMENT CAMPAIGN IN A MOUNTAIN REGION

The required $I/I_0$ normalized radiance can be measured with relatively simple broadband single-channel radiance detectors, as e.g. the widely used Sky Quality Meter (SQM) of Unihedron (Grimsby, ON, Canada), and the Telescope Encoder and Sky Sensor (TESS-W) developed by the European Union’s Stars4All project (Pravettoni et al. 2016; Zamorano et al. 2016; Hánel et al. 2018; Bará et al. 2019b). The linear distance between the base station and the elevated one should be at least a few hundred meters, to achieve the instrumental detection limit for a measurable NSB change.

A field experiment has been carried out in the High Tatra region (Slovakia) during late autumn 2019 (from Nov. 14 to Nov. 15) with snow cover absent. Since it was in the full moon period we limited our experiment to the first hour of astronomical night (from 6:00 PM to 6:50 PM). The Sun was 18° to 26° below the horizon, while the Moon was between 2° and 10° above the horizon, however, physically out-of-sight because of the presence of clouds near the horizon and obstacle blocking at low elevation angles. The cloud-free region spanned a wide area of the sky, with stable clarity around zenith. The base station was close to Tatranská Lomnica (850 m a.s.l.), a small town connected by cableway with the elevated station at Skalnaté pleso (1780 m a.s.l.). Skalnaté pleso is the midpoint between the base station and Lomnický peak. Located almost 900 m above the base station (see Fig. 3) and small plateau around the astronomical observatory, Skalnaté pleso is an ideal platform to make the measurements suggested in this paper. The SQM1 sensor was installed in an open space aside the city, but close to the cableway (likewise SQM2). The measured ground-normalized zenith radiance was $I/I_0 = 0.22 \pm 0.05$. The absolute maximum uncertainty of 0.05 was derived from the SQM error which is ±10% (as reported by manufacturer), while the value is doubled when determining the ratio of two radiances taken under different conditions by two different SQM devices (20% of 0.22 is 0.044; we rounded it up to 0.05). The $AOD$ was obtained from the AERONET station located in Poprad-Gánowce (49.03500° North, 20.32200° East), approximately 15 kilometres apart. This is advantageous since no satellite data were needed. The horizontal distance between the base station (SQM1: 49.16615°N, 20.26868°E) and the elevated station (SQM2: 49.18833°N, 20.23277°E) is only 4 km, which make us believe that the aerosol changes are mostly due to vertical stratification and not to the geographical distance. Normally two distant sites (tens of kilometres away) may differ in aerosol systems because the aerosol properties tend to decorrelate at such distances. This effect seems to be of minor relevance for the small area analysed here. The city of Poprad is really the only important light- and air-pollution source in the vicinity of the measuring site (see Tab. 1).

The measured value $I/I_0 = 0.22$ in combination with the AERONET record $AOD \approx 0.28$ provides the final estimate $\Delta AOD \approx 0.18 \pm 0.06$ (compare to Fig. 1). The uncertainty margin is derived from the amplitude of the diurnal fluctuation of $AOD$, strongly related to the near-surface pollutant mixing in the area. Due to the short horizontal distance between SQM1 and the AERONET station we assume that the $AOD$ uncertainty is comparable to the amplitude of its diurnal fluctuation. Although AERONET measurements in Poprad-Gánowce are given for the wavelength 500 nm, the conversion to 530 nm is simple through Ångström exponent $\alpha$. The values of $AOD$ at 530 nm and 500 nm are almost identical since $\alpha$ was as low as 0.06 on Nov. 14, 2019. The value of the $\Delta AOD \approx 0.17$ was inferred from $\Delta AOD$, taking into account $\Delta ROD = 0.118 (e^{-h_1/8} - e^{-h_2/8})$ is 0.011 for $h_1=0.9$ km and $h_2=1.78$ km. Although the SQM1 site could be classified as a high-elevation station, the $AOD$ values are not low because the mean altitude of the surrounding terrain is about 700 m a.s.l., and most of the air pollution sources are based on that level or even higher. The aerosol concentration normally peaks in the lower atmospheric layer, a few hundred meters thick, and in our case extending from 700 m upwards. The base station is only 100-200 m above the significant air pollution sources, so an impact from the greatest concentration of aerosols is not excluded in our experiment. We therefore expect that the performance of our method in this experiment can be representative for other sites, including places located at lower altitudes. Note that $AOD = 0.28$ is a value as high as in most of polluted regions, and definitely much higher than the one typically recorded thousand of meters above ground level.

|          | latitude (North) | longitude (East) | elevation (m) | distance (km) |
|----------|-----------------|-----------------|--------------|---------------|
| SQM1     | 49.166150       | 20.268686       | 903           | -             |
| SQM2     | 49.188333       | 20.232778       | 1780          | 4             |
| AERONET  | 49.035000       | 20.322000       | 706           | 15            |
| T. Lomnica | 49.155300   | 20.278800       | 850           | 1             |
| Poprad   | 49.059444       | 20.297500       | 672           | 12            |
| Smokovce | 49.140974       | 20.221024       | 1010          | 5             |

Table 1. Geographic coordinates and altitudes of the SQM, AERONET station and the main cities/towns present. The distance to the SQM1 installed at the base station is also provided.
I/I

if official sources are model-dependent, the ratio solving the theoretical radiative transfer models with the developed by extracted from the measurements. This can be done using an fuse sources like zodiacal light and the unresolved star back-

wise, the natural radiance contribution from the airglow, where the scattered light from artificial sources clearly ou-

to be much less sensitive to particular model choices. In turn, the highly variable columnar atmospheric optical
depth has been identified as the important driving fac-
tor of the short-term changes in the NSB amplitude. Based
on this finding we have developed a practicable scheme for
aerosol optical depth retrieval in the lower atmosphere dur-
ing a clear night, using the zenith sky brightness measure-
ments acquired by two observing stations at the bottom and
top of the atmospheric layer whose characterization is sought
for. Although the specific values for I and I₀ obtained by
solving the theoretical radiative transfer models with the
constraints imposed by the available information on the arti-
ficial sources are model-dependent, the ratio I/I₀ is expected
to be much less sensitive to particular model choices.

This method can be advantageously applied in clear and
moonless nights in locations close to artificially lit nuclei,
where the scattered light from artificial sources clearly out-
performs the direct radiance from natural sources. Other-
wise, the natural radiance contribution from the airglow,
pontlike sky objects like the planets and stars, and dif-
fuse sources like zodiacal light and the unresolved star back-
ground of the Milky Way and other galaxies shall be sub-
tracted from the measurements. This can be done using an
adequate celestial sky brightness model as, e.g. the ones de-
veloped by Leinert et al. (1998) or Durisoe (2013).

The proposed method, in combination with relatively
affordable airborne platforms like drones or low-altitude bal-
loons, seems to be well suited for recording continuous pro-
files of aerosol concentration at night. A large number of
researchers in the academic light pollution research commu-
nity routinely measure the night sky brightness at a wide
set of locations distributed throughout the world. This data
gathering effort is enhanced by the still larger number of
citizen-scientists that record in a permanent way the sky
brightness in the vicinity of their hometowns or astronomi-
oberving sites. Overall, this paves the way for enhanc-
ing data sharing between the light pollution and the atmo-
spheric research communities, whose fields of work are es-
entially intertwined.

5 ADDITIONAL REMARKS

As pointed out above, the zenithal artificial NSB depends,
among other parameters, on the angular emission function,
the spectral power distribution, and the spatial distribution
of the city lights. Although often imprecisely known, the
values of these parameters typically change slowly and pre-
dictably, or are even constant from night to night in a given
city. In turn, the highly variable columnar atmospheric optical
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6 CONCLUSIONS

The nighttime aerosol optical depth of arbitrarily thick lay-
ers of the lower atmosphere can be determined by measuring
the artificial sky brightness produced by city lights, avoiding
that way the limitations imposed by the absence of an ade-
equate reference natural light source. The method is based
on the general properties of the solutions of the radiative
transfer equation for the atmospheric propagation of arti-
ficial light from sources on the Earth surface, and is valid
for a wide range of values of the aerosol optical depth. Its
practical application requires relatively simple observational
data, namely the artificial sky radiance at the zenith mea-
sured at the two altitudes defining the limits of the layer,
usually starting from a ground-based station. Single-channel
low-cost radiance detectors can be used to that end.

A field experiment was conducted in the mountain re-

region of High Tatra (Slovakia). The ground-normalized zenith
brightness, along with the $AOD \approx 0.28$ retrieved from
the nearby AERONET station, were used to determine the
aerosol content $\Delta AOD \approx 0.17$ of the lower atmospheric layer
comprised between the two detectors (Fig. 3). The mapping
from the ground-normalized zenith brightness to the differ-
ential optical depth $\Delta OD = \Delta AOD + \Delta ROD$ (see Fig. 1)
was obtained by running a multiple scattering code (Kocifaj
2018). Due to its high stability, the Rayleigh-component
($ROD$) was determined from its theoretical formula, by as-
suming a molecular atmosphere scale height of 8 km. We
have found in our experiment that $\Delta OD \approx 0.18$ with an
uncertainty of 0.06, related to the uncertainty of $AOD$ as
described in the last paragraph in Sec. 4.

The aerosol optical depth is a commonly available satel-
ite product, so it can advantageously be used to retrieve
$\Delta AOD$ by applying the method here described. The char-
acterization of the aerosol content of the lower atmosphere is
relevant for light pollution research because it significantly
conditions the propagation of artificial light into the noc-
turnal environment, and hence the range up to which the
light from artificial sources can modify the night sky bright-
ness. We expect this work will have a direct impact on light
pollution modelling by providing additional information on
aerosols that was largely missing for many places over the
world. The limiting factor for the applicability of the method
is the requirement that the artificial sky glow dominates the
total radiance, i.e. that it be substantially larger than the
natural background.

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Figure 3. Configuration of the field experiment in a mountain re-

gion. The vertical separation ($h$) between the base (SQM1) and
the elevated station (SQM2) is chosen to be a few hundred me-
ters. The city emits light upwards, while the detectors (SQM1 and
SQM2) measure the backscattered light from the zenith region,
within a Gaussian field-of-view with full-width at half-maximum
(FWHM) 20°. NSB1 and NSB2 are the hemispherical night sky
brightness distributions at both stations, projected onto a hori-

zontal plane. The zenith is located at the center of each projection.

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5

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DATA AVAILABILITY STATEMENT

AERONET data are publicly available on aeronet.gsfc.nasa.gov. The numerical results for Fig. 1 and the all-sky NSB were computed using the model available in Kocifaj (2018). We did not use any new data.

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