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The spectral amplification effect of clouds to the night sky radiance in Madrid

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ABSTRACT

Artificial Light at Night (ALAN) may have various environmental impacts ranging from compromising the visibility of astronomical objects to the perturbation of circadian cycles in animals and humans. In the past much research has been carried out to study the impact of ALAN on the radiance of the night sky during clear sky conditions. This was mainly justified by the need for a better understanding of the behavior of ALAN propagation into the environment in order to protect world-class astronomical facilities. More recently, alongside to the threat to the natural starry sky, many issues have emerged from the biological science community. It has been shown that, nearby or inside cities, the presence of cloud cover generally acts as an amplifier for artificial sky radiance while clouds behave as attenuators for remote observers. In this paper we show the spectral behavior of the zenith sky radiance amplification factor exerted by clouds inside a city. We compare in-situ measurements made with the spectrometer SAND-4 with a numerical model applied to the specific geographical context of the Universidad Complutense de Madrid in Spain.

1. Introduction

Over illumination of the night sky is developing much faster than originally expected and so requires a thorough treatment and investigation. Artificial lights are identified as main sources of sky glow. However the extent of sky radiance largely depends on meteorological conditions. Astronomers in search of appropriate sites for night sky observations were the first to perform analyses of the ALAN, studying the problem specifically under clear sky conditions [1–7]. However the artificial light in nocturnal environments also has adverse consequences on light sensitive organisms by inhibition of melatonin and alteration of biological rhythms [8–12].

All physical bodies have the ability to reflect, absorb and scatter electromagnetic energy; particles suspended in the Earth's atmosphere are no exception. For a clear sky air molecules and aerosol particles are the main determinants of artificial sky brightness. However clouds can change the overall illumination substantially by adding reflected light to the scattered light causing the radiation reaching the ground to be a superposition of both components. In fact it is a non-trivial task to estimate the weighted contributions of these components given that each depends on the other.

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The lower the altitude of a cloud base the smaller the flux of scattered radiation is likely to be. This effect is due to decreased volume of the under-cloud atmosphere as rays of light have a lower probability of undergoing scattering events. Cloud reflectance is closely related to the cloud physics being dependant on factors such as cloud water content and droplet or ice particle size distribution. Further, light scattering in an under-cloud atmosphere is also a complex function of particle shape and size distributions, material compositions and internal mixing of individual materials, thus resulting in wide range of scattering patterns. Routine observations indicate that an overcast atmosphere can exhibit a significantly increased amount of artificial sky radiance due to diffuse reflection by the cloud layer. This effect is usually referred to as amplification and quantified through the so-called cloud amplification factor (AF). The analysis of ALAN propagation is thus conceived as a complex process that involves effects of different natures [13].

Garstang [14–16] was one of the first researchers to recognize the role of atmospheric physics in determining night sky radiance, determining empirically the zenith radiance increase in the center of a city. More recently, and with the aim of deepening understanding of this effect, diverse field experiments and theoretical simulations have been conducted in order to determine the connection between optical properties of the atmosphere and the amplification of artificial sky brightness [17–20].

Another priority research area for the understanding of sky radiance under cloudy conditions, specifically the high variability of amplification factors observed worldwide, is the verification of the existence of a link between the lighting technology, the environment, radiance data and the over-illumination concerns. Regional and global change in artificial lighting is a pressing environmental problem in urbanized regions with constantly growing population. So the target in light pollution research is not only the identification of the basic features of night sky radiance but also uncovering the fundamentals of optical effects involved in forming the diffuse a light field under nighttime conditions. However this is only possible if spectral characteristics are analyzed.

In this paper the spectral radiance is determined experimentally and interpreted theoretically under controlled conditions taking into account optical properties of aerosol particles in a local atmosphere (obtained from in-situ Aerosol Robotic Network data, (AERONET)), locality-specific light source inventory and data from the Visible Infrared Imaging Radiometer Suite (VIIRS) satellite sensor. All these data form a complementary data set and this is the first time that such comprehensive experiments have been carried out during field campaigns. The accumulated experimental data allows for advanced validation against theoretical predictions.

Routine night sky observations are most typically performed using low-level broadband radiometers such as the Sky Quality Meter (SQM). Therefore the information on the spectral behavior of sky radiance is largely lost. Instead a band-averaged radiance is derived by integrating the light signals over the full wavelength range of the SQM. Such integration distorts spectral features of the scattered light thus precluding any deeper interpretation of experimental data. Note that basic formulae for radiative transfer are valid only for monochromatic or quasi-monochromatic radiation. It is the intention of this study to determine spectral behavior of the amplification factor and to analyze its behavior in relation to the optical properties of the atmosphere of a locality in the Madrid area. This region is of particular importance, not only because Madrid is an extremely bright city, but also because it has well known sources of light pollution thus reducing uncertainties otherwise arising from uncertainties in the lighting technologies inventory. Further questions that addressed in this work are: what is the range of AF values observed throughout the visible spectrum, what is the role of cloud altitude in the amplification phenomenon and to what extent the theoretical model can explain the experimentally determined AFs? Last but not least is whether our findings can be generalized into a rule that can help to understand observational data from other regions.

2. Methods

2.1. Experimental context

Madrid is the brightest capital of Europe in terms of illumination density ($\sim$115 nW/sr/cm^2) according to the Visible Infrared Imaging Radiometer Suite (VIIRS) satellite sensor [21] on board the Suomi National Polar-orbiting Partnership weather satellite. Madrid's illumination technology for street lighting, according to the Madrid town hall inventory, is 100% HPS lamps. In addition to this inventory there are also private and ornamental lights. According to [22], 60% of the city area is illuminated with either public street lighting or private/ornamental lights, which is more than any other capital examined [22]. Madrid has been widely studied since 1994 with more than 21 scientific studies related to its light pollution [22]. Several instruments are installed on top of the physics faculty building of the Universidad Complutense de Madrid (UCM) which makes UCM as an ideal site for our study. Night sky brightness measurement devices are generally located in dark places where the contribution of natural sky brightness such as the moon or stars is predominant [23,24]. In the case of Madrid artificial sky radiance clearly dominates sky brightness. This is another reason that render Madrid as one of the best sites to conduct this study.

2.2. Observation platform at UCM

The astronomical observatory of the UCM (IAU-MPC code I86) is located inside Madrid City in Ciudad Universitaria in the north east around 4 km from the city center and 6.7 km from what we estimate as the light center of mass of the metropolitan area. The observatory domes were built on the rooftop of the Physics building which has enough space to accommodate more astronomical instruments. The observatory suffers from the light pollution of Madrid metropolitan area which is the main pollutant source of the region (Comunidad de