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# The effect of the spectral response of measurement instruments in the assessment of night sky brightness

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ABSTRACT

This paper deals with the errors and uncertainties in skyglow measurements caused by the variation of sky's spectrum. It considers the theoretical spectral response of common instruments that are used for light pollution assessment. Various types of light sources were used in this investigation. This study calculates the spectral mismatch errors and the corresponding correction factors for each combination of instrument and light source. The calculation method is described and the results are presented in multiple figures. Calculated data show a big variation in potential errors that can be introduced when comparing readings of diverse instruments without considering the variation of sky's spectrum. This makes the spectral data of the sky a mandatory input to the dark sky assessment. Useful conclusions, related to instruments with better or worse behaviour, are derived from the calculations. The paper also includes suggestions on how to conduct multi-instrument measurements with or without spectral data.



## 1. Introduction

Artificial light at night (ALAN) is constantly increasing around the world. A recent research [1] revealed that the lit surface of Earth is increasing in brightness and extend despite the renovations of lighting installations that were widely implemented. This is mainly caused by the rebound effect of price competitiveness of LED light sources compared to traditional gas discharge lamps [2]. The excess of light in outdoor lighting leads to the so-called light pollution and to the waste of energy [3]. Light pollution can be observed either from ground level or from space via remote sensing [4]. A major effect of light pollution is the increase of the skyglow during the night. The intensity and the variation of skyglow depends on the number, the concentration and the type of artificial light sources [5–7]. Weather conditions and cloud coverage also affect the brightness of a light polluted sky [8]. Researchers concluded that light pollution has an environmental impact [9] and is affecting human circadian cycle [10,11]. A recent research links also the ALAN with breast and prostate cancer risk [12]. Thus, the monitoring and the evaluation of light pollution is of high scientific interest and a challenging topic for environmentalists, biologists, anthropologists, astronomers, engineers, etc.

The assessment of light pollution includes the measurement of dark sky brightness. The current trend is to monitor the skyglow using various types of instruments. The most common instruments are presented in the next chapter. The target is to investigate how much "bright" is the sky during the night and how this brightness varies across different areas, time, and period of the year. Measurement of brightness includes the radiation in the region of visible lighting (approx. 380–780 nm). An accurate assessment of light pollution can be useful in case of light remodelling and infrastructure renovation [13,14].

This task could have good accuracy and repeatability if sky's spectrum was constant during twilight and night period. However, the spectrum of the sky is not stable due to natural and artificial light variation. In addition, sky spectrum close to horizon may be significantly different compared to the spectrum at zenith. This is due to physical reasons but mainly depends on the artificial lighting installations where upward lighting scatters in the atmosphere. The scheduling of city lights switching on and off, grouped in various source types, affects the spectrum synthesis of the skyglow. Light pollution is also reflected in the clouds during night-time. The recent trend of replacing street luminaires is also a parameter that changes the type of emitted light in certain areas of a city.

Thus, using instruments with different spectral behaviour introduces potential uncertainties and non-repeatability of measurements. Considering that the light pollution deals with the effects of ALAN in humans, animals, insects and plants, shows that assessment of skyglow is a complicated procedure which can easily lead to confusing results. Especially in cases where instruments are used to monitor the dark sky for long periods, the comparison of these measurements cannot be considered valid.

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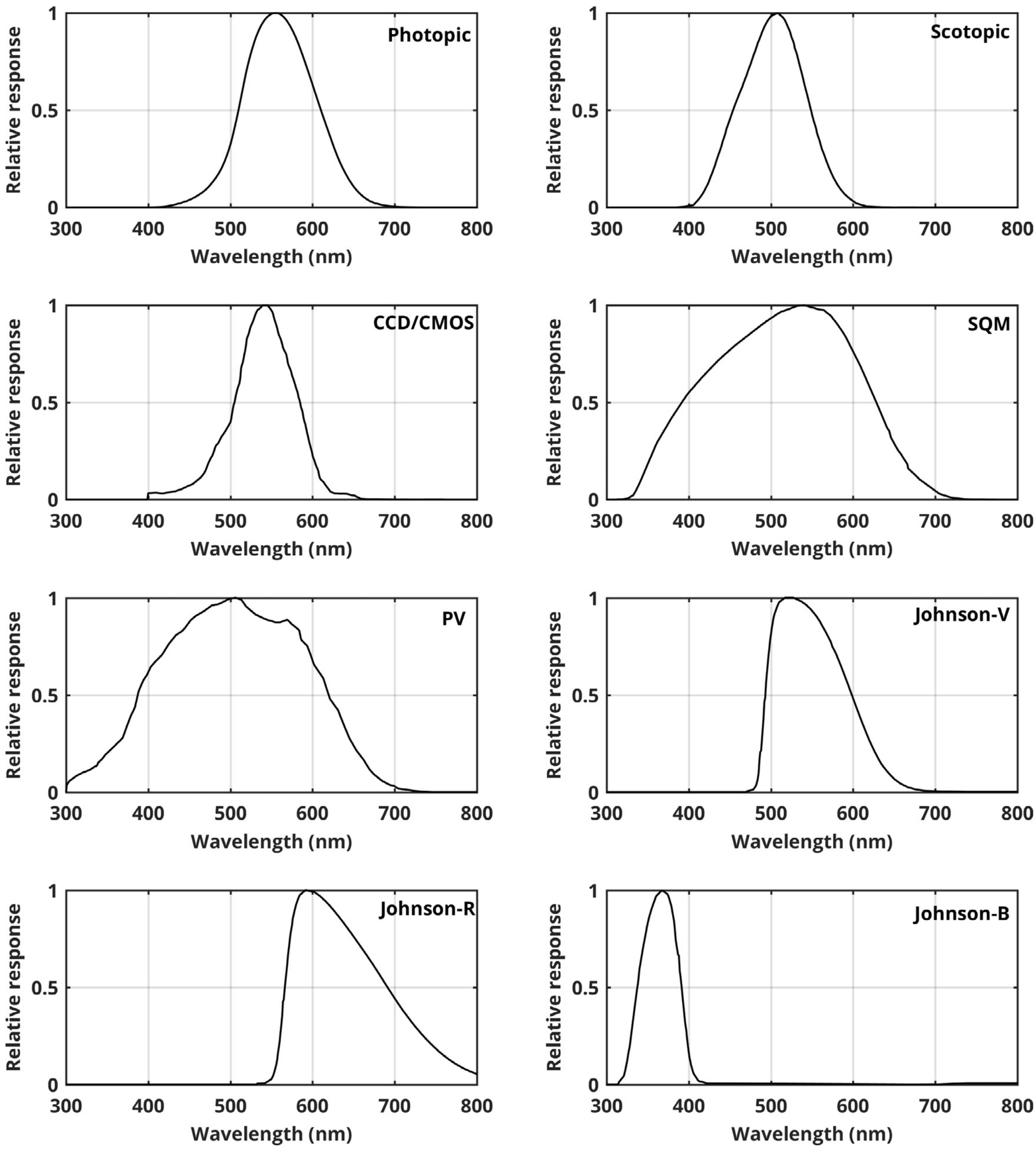


**Fig. 1.** Typical spectral response of the investigated instruments.

This paper investigates the theoretical correlation between the measurements from instruments that are used for skyglow assessment. The study considers a variable spectrum of the sky. Instruments under consideration are equipped with different filters like photopic, astronomical or custom ones. It illustrates the variation between factors that can be used for spectral correction of different instruments. This research works towards the development of a scientifically acceptable skyglow assessment methodology.

## 2. Status quo in dark sky measurements

Dark sky brightness assessment can be realized by measuring the radiation in various spectral bands. In terms of light pollution research, several different procedures and instruments are used. A recent work [15] describes the current situation in this field and gives an analysis of the available instruments. From this work it is clear that there is no standardized instrument or measuring procedure for dark sky assessment. This is mainly due to the involvement of different scientists in the field of light pollution, where each one is using a different type of instrument. Several intercomparison campaigns, during LoNNe and Stars4All projects revealed the challenging and interdisciplinary work of dark sky assessment [16–18].

The instruments that are used in such measurement sessions are the following. One of the most common instrument is the Sky Quality Meter (SQM) [19–22]. SQMs use a single cell sensor and are equipped with a broadband filter. The field of view of this instrument is relatively narrow (~20–40°). The readings of SQMs are in astronomical magnitudes per square arcsec (mags/arcsec$^2$). A similar instrument, in terms of sensor's spectral response, is the "Lightmeter" (LM) based on a small PV cell [23,24]. LMs are extremely sensitive, waterproof, with 180° of angular response and are ideal for long-term monitoring of light pollution. Instruments with the human spectral response, like luminance meters, are also used to measure the brightness of the dark sky. These instruments are equipped with photopic CIE V(λ) or scotopic V' (λ) and the corresponding unit is candela per square meter (cd/m$^2$). All the