Study of the Spectral Response of Sky Quality Measurers

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Abstract: The aim of this project is to study the spectral response of two sky quality measurers, SQM and TESS-W, and compare the instrumental sky brightness obtained by these two photometers with the sky brightness obtained synthetically using its spectral response and night sky spectra from Montsec (Lleida), measured by SAND-4B spectrometer. We are going to analyze the difference between the magnitude measured by SQM and TESS-W to study if the atmospheric emission (airglow) at red wavelengths triggers the difference between the sky brightness measured by the previously mentioned instruments at the Montsec.

I. INTRODUCTION

The increase of urban areas added to the presence of artificial lighting has produced a rise in the sky brightness due to artificial light sources. The artificial light propagates through the atmosphere and could be detected more than 100 km away. One of the environmental consequences of the light-polluted areas is that the sky darkness is reduced, as a consequence of this, it is increasingly more complicated to appreciate the celestial objects at night near populated areas, disastrous for astronomical observations.

In order to preserve the sky darkness, the study of light pollution has become a growing field of study in astronomy. To quantize sky brightness several detectors have been developed. Two of them are SQM (Sky Quality Meter) displayed in Fig. 1 and the TESS-W photometer (Telescope Encoder and Sky Sensor) shown in Fig. 2. These photometers are characterized by having an easy way to operate, having an Ethernet connection to a database and being affordable. The previously mentioned characteristics are practical to realize a mapping of sky darkness and to study its time evolution, particularly interesting in the surroundings of observatories, as these devices can be placed statically, perform continuous measurements and the data can be obtained remotely.

During my internship at PAM (Parc Astronòmic Montsec) supporting the follow-up campaign of the night sky quality testing, the new TESS-W installed at the roof of PAM was noticed that at the Montsec, where PAM is located, the magnitude of the sky brightness measured by TESS-W and SQM differed between 0.2 and 0.4 $mag/arcsec^2$. The results obtained from measuring the sky brightness with SQM and TESS-W are popular to be similar, to the point of being comparable. At first, the hypothesis that came out to explain this difference in the magnitude measured was that the new TESS-W photometers might have some fabrication problem or a calibration error. Discussing that hypothesis with Jaime Zamorano and some members of his team, manufacturers of TESS-W (Universidad Complutense Madrid), the calibration or assembly of the photometers did not seem to be the problem.

TESS-W and SQM are two different instruments with different spectral responses, as shown in Fig. 3, and the Montsec spectrum has a characteristically high red line (produced by airglow). So the brighter magnitudes values obtained by TESS-W could be due to the band-pass of TESS-W being higher at red wavelengths than the SQM.

In view of these facts came out the idea of realizing a study of the spectral response of SQM and TESS-W photometers using spectra of Montsec and comparing the results with the instrumental data, to check if the difference has its origin in the airglow red line of the Montsec spectrum, discarding other possible issues as ageing of the photometers. To analyze the spectral response, spectra of Montsec measured by SAND-4B spectrometer, exhibited at Fig. 4, will be used (for more details see section II C).

II. INSTRUMENTS

A. Sky Quality Meter

The Sky Quality Meter (SQM) is manufactured by Unihedron (Canada). This instrument is based on a frequency to radiance converter chip TSL237(ams AG, Premstaetten, Austria) and is calibrated in the AB magnitude system. The spectral response of SQM is similar to the photopic eye response with a band-pass from 350 to 1000 nm, and a field of view with approximately a Gaussian profile with Full-Width Half Maximum (FWHM) $\approx 20°$. The aforementioned instrument performs sky brightness measurements in units of $mag/arcsec^2$ continuously with an integration time $\approx 60\,s$ [5]. The sky brightness data recorded by SQM can be obtained remotely in real-time as it disposes of an ethernet connection. The SQM disposes of housing to protect the instrument from the climate conditions, the effect of the lens of the housing is removed from the magnitude results applying an additional zero point.

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FIG. 1: SQM.

B. Telescope Encoder and Sky Sensor

The Telescope Encoder and Sky Sensor (TESS-W) is a photometer developed by the European Union's Stars4All project. This instrument uses a TSL237 light-to-frequency converter, as SQM calibrated in the Absolute magnitude scale (AB), to set a zero point in which the magnitude measured has physical meaning. Its band-pass goes from 350 to 800 nm, and the field of view is approximately a Gaussian profile with Full-Width at Half Maximum (FWHM) ≈ 17° [2]. The data recorded by these devices, in units of $mag/arcsec^2$, can be consulted in real-time at the TESS-W photometer network [6].

FIG. 2: TESS-W photometer.

From the transmission curve of TESS-W and SQM that appears in Fig. 3, we can appreciate that the spectral response of TESS-W is close to 1 in mostly all of its range meanwhile the transmittance of SQM decays at red wavelengths.

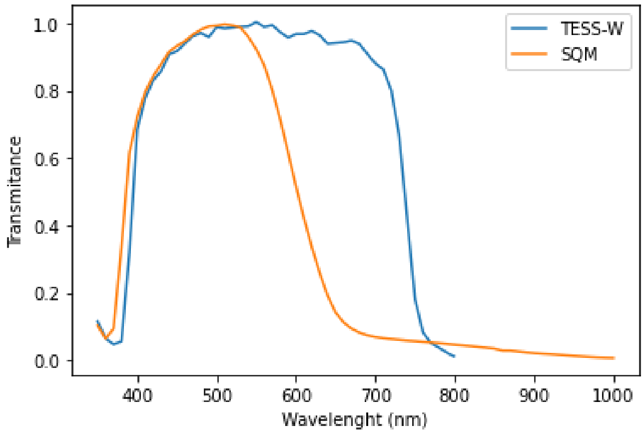

FIG. 3: Spectral response in function of wavelength of TESS-W and SQM.

C. SAND-4B Spectrometer

The SAND-4B is a spectrometer adapted to operate in dark places, it has a spectral resolution of 0.5 nm and its spectral range is from 400 to 730 nm. The instrument is composed of a CCD camera and SBIG's DSS-7 long-slit spectrograph. The slit covers a field of ≈ 2° and the exposure time is 7200s (2 hours)[3].

We use the SAND-4B spectrometer to compare the synthetic magnitude obtained from the Montsec night spectra using the spectral response of SQM and TESS-W with the instrumental data measured with the photometers the same night. Due to problems with the shutter, calibration errors and other issues, SAND-4B has not had a quality spectrum since mid of 2020, so there are no Montsec night spectra for the dates that TESS-W has been operative. For this reason, in this project, the spectra used are from 2015, shown in Fig. 6. We are assuming that the use of spectra of another period of time does not affect the results of the project for the reason that we suppose that the night sky conditions of Montsec have not changed significantly as it is a Starlight certificated region.

To perform the synthetic photometry were used five spectra from SAND-4B. Two of the spectra, 2015-02-07 and 2015-11-30, have higher spectral radiance than the other spectra because of the moonlight contribution shown in Fig. 6. Some spectra (2015-11-30 and 2015-12-03) show a wavelength shift around 8 nm, due to an auto-calibration issue. As it is a small displacement and we are doing broad-band photometry, we are assuming that the effect in the magnitude calculation is negligible.

III. INSTRUMENTAL MEASUREMENTS

During the testing of TESS-W was noticed that magnitude measured by TESS-W (m_{TESS}) was brighter than

FIG. 4: SAND-4B spectrometer with housing removed.

the magnitude measured by SQM (m_{SQM}). The instruments are located one next to the other ergo, the difference in sky brightness is not due to different locations as they are pointing to the same region of the sky.

In Fig. 5 we can see plotted the magnitude measured by six different TESS-W and two SQM detectors during the night of 2021-08-13. We can appreciate that the magnitude of SQM is darker than the magnitude of TESS-W, and the difference between each kind of photometer approximately remains constant.

For this analysis, we use two SQM, SQM-Baltasana which is an SQM that was temporarily in testing in parallel with SQM-XCL, which is an SQM of the Catalonian network of sky brightness measurements. We have to take into account that the SQM-XCL which has the darker measurements is aged so its lens has darkened due to meteorological conditions, as it is been placed outdoors for several years. SQM XCL and Baltasana have applied an offset of $-0.392\,mag/arcsec^2$ and of $-0.203\,mag/arcsec^2$, respectively. The data of the TESS-W is obtained from the web page [6], where are stored all the TESS-W data measurements.

To illustrate this difference, the Table I shows the average instrumental magnitude of the night of 2021-08-13. The average magnitude of SQM installed at that moment are for SQM-XCL, $m_{SQM,1} = 21.605$, and for SQM-Baltasana, $m_{SQM,2} = 21.513$, where $\Delta m = m_{TESS} - m_{SQM}$.

Apart from TESS-W and SQM, we have used SAND-4B to obtain the night sky spectra to perform synthetic photometry to compare the results with the photometric measurements. The spectra were measured by the SAND-4B established on the roof of PAM where the SQM

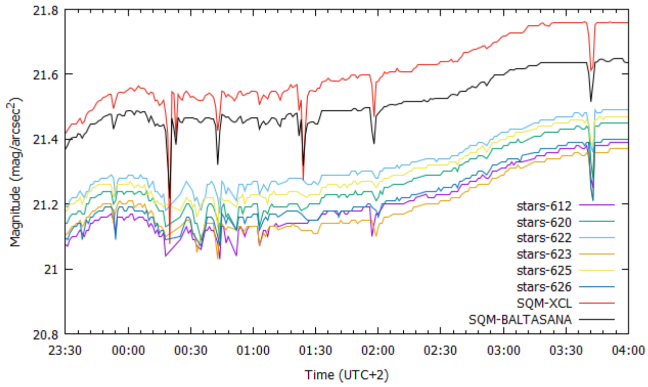

FIG. 5: Sky brightness magnitude of six TESS-W, labeled as "stars" and two SQM from night of 2021-08-13.

TESS-W	m_{TESS}	Δm_1	Δm_2
Stars-612	21.211	-0.394	-0.302
Stars-620	21.267	-0.338	-0.246
Stars-622	21.325	-0.280	-0.188
Stars-623	21.204	-0.401	-0.309
Stars-625	21.302	-0.303	-0.211
Stars-626	21.219	-0.386	-0.294

TABLE I: Average instrumental magnitude obtained by six TESS-W photometers and its difference to the average instrumental magnitude obtained by two SQM, in units of $mag/arcsec^2$.

and TESS-W are as well installed. Although each instrument has a different field of view, nevertheless, we assume that the amplitude of the field of view does not affect the results significantly. All the instruments are pointing to the zenith 0° furthermore, the sky at the region we are analyzing is slightly light-polluted hence, the artificial skyglow effect is negligible near zenith angles between 0-20 degrees. For that reason, we can disregard the difference between the field of view of the instruments.

A. Atmospheric Airglow

Apart from light pollution, there are natural light sources that produce sky brightness. Besides astrophysical sources, such as stars and the Milky Way, the decay of excited states triggered by solar high energy radiation produce the airglow, a light emission in the upper layers of the atmosphere.

In Fig. 6 we can see several spectra of Montsec night sky. The dashed lines correspond to wavelengths where the sky brightness increase due to airglow. We can notice the OI green line at 558 nm where the height of the emitting layer is 90 km and the OI red lines at 630 nm and 636 nm where the height of the emitting layer is 250-300 km [1].

We can appreciate in Fig. 7 that whereas the trans-

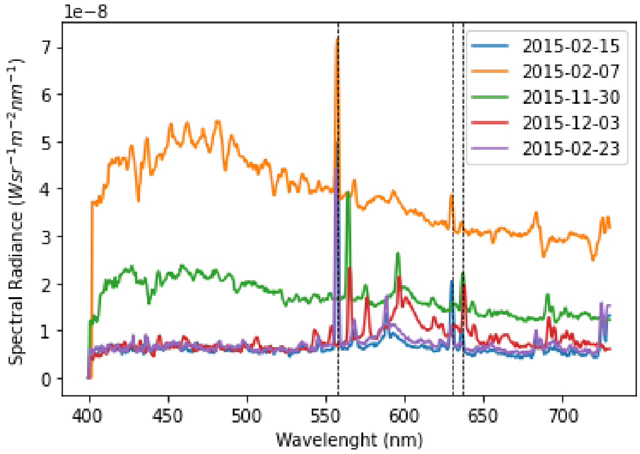

FIG. 6: Spectra of Montsec night sky from 2015 measured by SAND-4B.

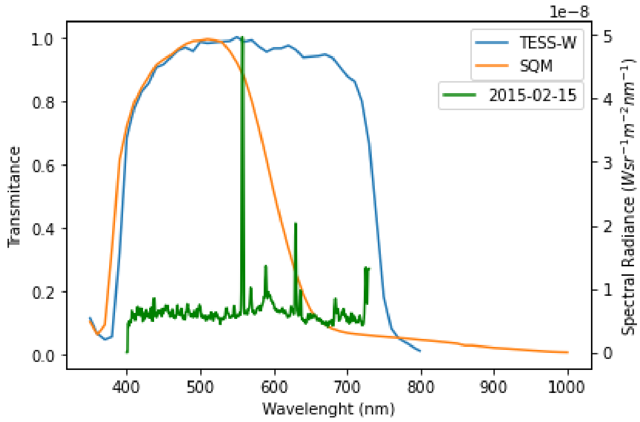

FIG. 7: Spectral response of TESS-W, SQM and superposed spectrum of Montsec obtained by SAND-4B.

mittance is near to one at the OI green line for the two photometers, at the red line of wavelength 630 nm the transmittance of TESS-W is approximately 1 meanwhile for the same wavelength the transmittance of SQM is approximately 0.25. The result of the synthetic photometry will prove if this atmospheric emission band at the spectra produces a significant change in the values of the magnitude obtained by SQM and TESS-W or instead, discard this factor as the source of the difference in the instrumental measurements of these photometers.

IV. SYNTHETIC PHOTOMETRY

Taking into account that the zero points of SQM and TESS-W are defined from the AB magnitude system [4], the same system has been used to calculate the synthetic magnitude from the band-pass of each photometer, described at (1),

$$AB = -2.5\log_{10} f_\nu + 48.60, \tag{1}$$

which is defined by a monochromatic flux density of $f_\nu = 3631\,Jy$ where $1\,Jy = 10^{-26}\,WHz^{-1}m^{-2}$.

Seeing that the transmittance of the filters is expressed in function of wavelength instead of frequency, the reference flux becomes $f_\nu(\lambda) = c\,\lambda^{-2} \times 3631 \times 10^{-26}$. The reference spectral radiance in AB scale is $L_{\lambda,AB} = f_\nu(\lambda) \times \Delta\omega_0^{-1}$, where $\Delta\omega_0$ corresponds to $1\ arcsec^2 = 3.3504 \times 10^{-11}\,sr$ [2]. From these expressions the reference radiance is,

$$L_{r,AB} = \int_0^\infty 3631[Jy]\frac{c}{\Delta\omega_0}\frac{T(\lambda)}{\lambda^2}d\lambda, \tag{2}$$

where c is the speed of light in vacuum.

The integrated radiance obtained for a filter by a spectra is,

$$L = \int_0^\infty L_\lambda T(\lambda)d\lambda, \tag{3}$$

where $[L_\lambda] = Wsr^{-1}m^{-2}nm^{-1}$ is the spectral radiance obtained with SAND-4B and $T(\lambda)$ is the transmission coefficient of the filter for each wavelength.

The magnitude in AB scale is given by

$$m_{AB} = -2.5\log_{10}\frac{L}{L_{r,AB}}, \tag{4}$$

where L is the sky radiance and $L_{r,AB}$ is the reference radiance at the AB system, both with magnitude of $Wsr^{-1}m^{-2}$, which are obtained from equations (2) and (3).

To perform the synthetic photometry I have made use of python language to code a simulation which calculates the integrated reference radiance in the magnitude system AB eq. (2) and the integrated radiance from spectra eq. (3) for the transmittance curve of each instrument (band-pass of SQM and TESS-W) and each spectrum. Applying these results to eq. (4) we can obtain the synthetic magnitude of TESS-W and SQM. This simulation can be executed to perform synthetic photometry with different filters and sky spectra as the program allows us to get the synthetic photometry in any filter if we know the transmittance curve. For the purpose of this project, the analysis has been limited to the filters of SQM and TESS-W with the spectrum of Montsec.

V. RESULTS

The values obtained by the simulation of the reference radiance at the magnitude system AB for each filter are exposed in Table II. The values of $L_{r,AB}$ seem coherent

Filter	$L_{r,AB}$	σ
TESS-W	522.8	6.5
SQM	422.7	6.5

TABLE II: Reference radiance of diverse filters obtained synthetically in the AB scale in units of $Wsr^{-1}m^{-2}nm^{-1}$.

with the results obtained at previous projects (see [2] as an example).

The results of the synthetic magnitude for each instrument and the difference between them, $\Delta m = m_{TESS} - m_{SQM}$, are shown in Table III. The magnitude obtained synthetically from the spectra has an uncertainty of $\sigma = \pm 0.014 mag/arcsec^2$.

Comparing the magnitude obtained synthetically with the instrumental magnitude we can appreciate that the difference between the two instruments persists, being the values obtained from TESS-W between 0.1 and 0.3 $mag/arcsec^2$ brighter than the obtained with SQM in both synthetic and instrumental magnitudes. These results indicate that the root of this difference must be from the red line at the Montsec spectrum inasmuch as performing synthetic photometry directly from the bandpass of the instruments factors like the ageing of the lens or their correct functioning and calibration are discarded. As previously mentioned the spectral response of SQM at red wavelength is ≈ 0.2-0.3 meanwhile the TESS-W is ≈ 1.

Spectrum	m_{TESS}	m_{SQM}	Δm
2015-02-15	20.942	21.168	-0.226
2015-02-07	19.069	19.209	-0.140
2015-11-30	19.956	20.107	-0.151
2015-12-03	20.759	21.070	-0.311
2015-02-23	20.834	21.074	-0.240

TABLE III: Synthetic magnitude obtained from SQM and TESS-W spectral responses.

In addition, recently, it has been reported that TESS-W magnitude measurement is brighter than expected in regions with a good sky quality meanwhile, in places with higher light pollution as cities, where the relative contribution of the airglow is almost null, the magnitude measured by TESS-W is very similar to the magnitude measured by SQM. In this project, we did not dispose of spectra from other locations. However, it would be interesting in future projects to study the spectral response of the previously mentioned instruments in cities and further places.

VI. CONCLUSIONS

- The analysis of the comparison of the instrumental and synthetic response of the photometers TESS-W and SQM using night sky spectra of a region with a characteristically dark night sky is not done in any previous project. With the results obtained performing synthetic photometry using SAND-4B spectra, we can conclude that the difference in the instrumental magnitude measured at Montsec by TESS-W and SQM has its source at the red line emission of the spectrum from airglow and the different spectral response at that wavelength.
- In Montsec night sky conditions these two instruments are not comparable and they must not be used indistinctly. In general, we must not compare the results of instruments with a different spectral responses. However, this particular case is especially relevant as in dark night sky regions we can detect atmospheric phenomena, such as airglow, that contribute to the sky brightness.

Acknowledgments

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