Night Sky Photometry with Sky Quality Meter

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ABSTRACT

Sky Quality Meter, a low cost and pocket size night sky brightness photometer, opens to the general public the possibility to quantify the quality of the night sky. Expecting a large diffusion of measurements taken with this instrument, I tested and characterized it. I analyzed with synthetic photometry and laboratory measurements the relationship between the SQM photometrical system and the main systems used in light pollution studies. I evaluated the conversion factors to Johnson's B and V bands, CIE photopic and CIE scotopic responses for typical spectra and the spectral mismatch correction factors when specific filters are added.

Subject headings: light pollution – night sky brightness – photometry – instruments – calibration

1. Introduction

Measurements of artificial night sky brightness produced by light pollution are precious to quantify the quality of the sky across a territory, the possibility of the population to perceive the Universe where is living, the environmental impact of nighttime lighting and their evolution with time. However accurate mobile instruments do not fit requirements for wide popular use. They are expensive and, even if designed to be set up rapidly and to map the brightness on the entire sky in few minutes like WASBAM (Cinzano & Falchi 2003), they require transport, pointing, tuning, computer control. Compact mobile radiometers, like LPLAB's IL1700 (Cinzano 2004), require at least to carry around a 2.5 kg bag and to spend thousands of dollars. Unfriendly, bothering and time-consuming operations prevent frequent measurements by not professional users (and sometimes by professional users too) and high cost prevent purchases by individuals. As a result, so far many amateurs astronomers, activists of organizations against light pollution, dark-sky clubs, educators, environmentalists and citizens were unable to face with the quantification of the quality of the sky of their territory.

Unihedron Sky Quality Meter (thereafter SQM), a low cost and pocket size night sky brightness photometer, opens to the general public the possibility to quantify the quality of the night sky at any place and time, even if with different accuracy and detail from professional instruments. Expecting that measurements taken with SQM be widely diffused, I tested and characterized the instrument in order to well understand how they relate to usual measurements. I studied the effects of the instrumental response on the measurements of light pollution based on synthetic photometry and laboratory tests carried out with the equipments of the Light Pollution Photometry and Radiometry Laboratory (LPLAB). I evaluated for typical spectra the conversion factors to photometric systems used in light pollution studies, like Johnson's (1953) B band, V band, CIE photopic and CIE scotopic responses. I also checked the spectral mismatch correction factors when specific filters are added.

Results presented here should be taken only as an indication because LPLAB equipments were not made to check instruments with uncommonly large aperture angle and response under 400 nm.

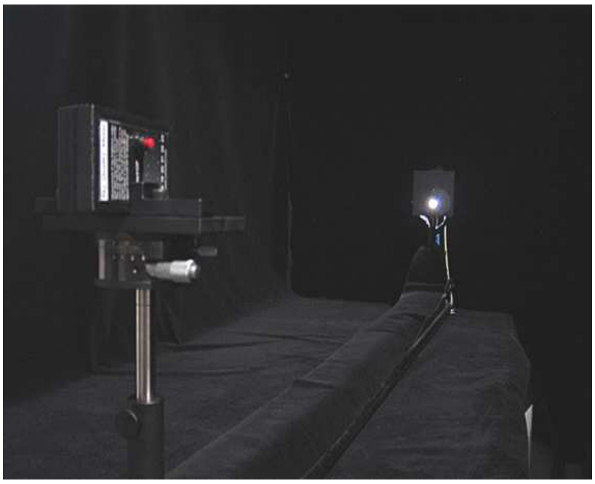

Fig. 1.— Measurement of the acceptance angle.

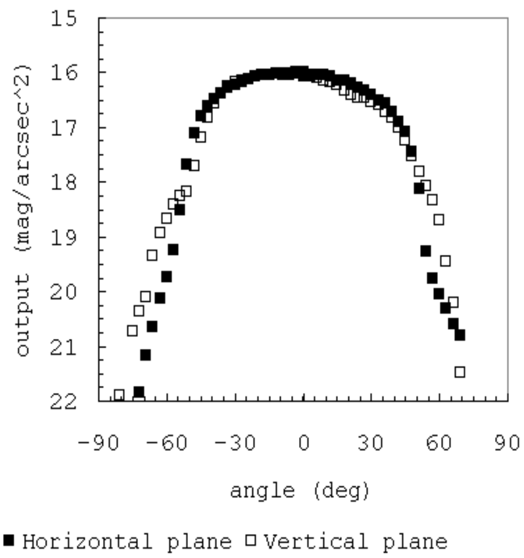

Fig. 2.— Angular response of SQM in magnitudes. Angles are positive downward and rightward.

Residual background ambience light could contaminate some data and the sensitivity of the response calibration equipment is low under 400 nm.

2. Acceptance angle

I checked the acceptance angle of the SQM serial n.0115 v.1.09 mounting it, both in horizontal and vertical position, on a rotation table (accuracy 0.01 degrees) placed at 1.289 m from a circular aperture with diameter 3.2 mm in front of LPLAB Spectral Radiance Standard (lamp 7) powered by the LCRT-2000 radiometric power supply (radiance stability 1% at 550 nm)(Cinzano 2003c, e). The set up is shown in fig. 1. Room temperature was maintained at 24.5±0.5 C. Background light has been subtracted.

The readings of the instrument at each angle are shown in fig. 2 in magnitude scale with arbitrary zero point. Open squares are data along the vertical plane, filled squares are data along the horizontal plane. Angles are positive below the middle plane and at right, like in the data tables of the detector manufacturer (TAOS 2004).

Fig. 3 shows the same readings in a linear scale normalized to its maximum. The figure also shows the normalized output frequency of the detector at each angle provided by the detector manufacturer (vertical is dashed, horizontal is dot-dashed). This quantity is proportional to the measured irradiance because the detector is a Light Intensity to Frequency Converter. The larger attenuation of light incident on the filter with increasing angle makes the SQM angular response slightly narrower than the detector angular response at large angles. The Half Width Half Maximum (HWHM) is ∼42 degrees. A factor 10 attenuation of a point source is reached after 55 degrees. Optical inspection shows that screening of the detector begins at about 60-65 degrees.

When comparing SQM measurements with measurements taken with small field photometers it should be taken into account that night sky brightness is not constant with zenith distance. In particular, artificial night sky brightness usually grows with zenith distance with large gradients. The brightness measured pointing the SQM toward the zenith will be the weighted average of brightness down to a zenith distance of 60 degrees, and then it will be greater (lower magnitude per square second of arc) than the punctual zenith brightness:

$$\overline{I} = \frac{\int_0^{2\pi} \int_0^{\pi/2} I(\theta,\phi) D(\theta) \sin\theta \, d\theta \, d\phi}{\int_0^{2\pi} \int_0^{\pi/2} D(\theta) \sin\theta \, d\theta \, d\phi} , \qquad (1)$$

where $\overline{I}$ is the measured average radiance, $D(\theta)$ is the angular response given in fig. 3 and $I(\theta,\phi)$

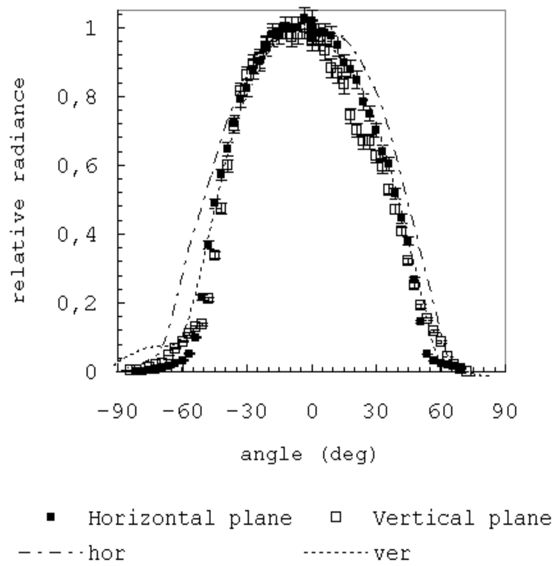

Fig. 3.— Angular response of SQM in a linear scale. Lines show the normalized output frequency of the detector at each angle provided by the detector manufacturer, along the vertical (dashed) and horizontal (dot-dashed) planes.

is the radiance of the night sky in the field of view of the SQM. Fig. 4 shows the weight function $D(\theta)\sin\theta$ for each angle of incidence θ. It is peaked at about 30 degrees because going from 0 to $\pi/2$ the angular response decrease and the integration area grows. The effect is still more important when pointing the SQM to zenith distances of about 30 degrees because the instrument will collect light from the zenith area down to the horizon. As an example, fig. 5 shows an estimate of the difference Db between the SQM average brightness and the punctual brightness at each zenith distance, based on a typical brightness versus zenith distance relationship at a polluted site measured by Favero et al. 2000 (in Cinzano 2000, fig.14) in Padova. It shows that at 30 degrees of zenith distance the SQM average brightness is brighter than the punctual brightness of -0.4 mag/arcsec^2. Measurements beyond 30-45 degrees of zenith distance (i.e. under an elevation of 60-45 degrees) should be avoided if the contamination by light sources and by the luminous or dark landscape under the horizon cannot be checked.

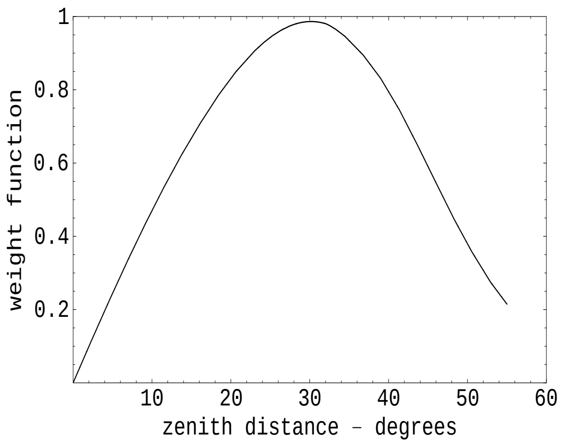

Fig. 4.— Weight of the radiance at each angle of incidence in the measured average radiance.

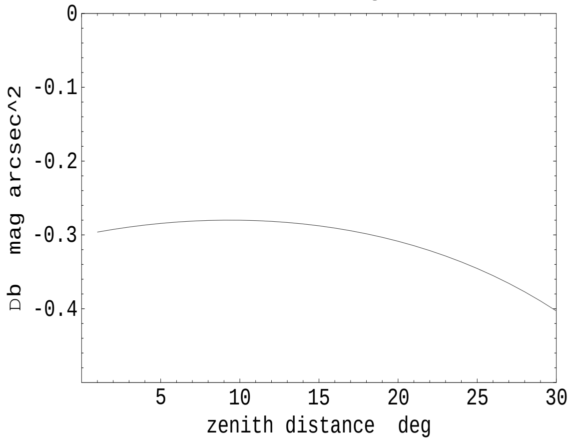

Fig. 5.— Difference between SQM average and punctual brightness for a typical polluted site.

3. Linearity

I checked the linearity of our SQM analyzing the residuals of a comparison with the IL1700 Research Radiometer over the LPLAB Variable Low-light Calibration Standard (Cinzano 2003c). Data are shown in figure 6.

The standard error is $2\sigma = \pm 0.028$ mag arcsec^{-2} corresponding to 2.6%. Linear regression has coefficient 0.0005. The uncertainty of the SQM due to deviations from linearity over a range of 12 magnitudes is likely smaller than 2.6%, because measurements are affected by the stability of the standard source (1%), the linearity of the reference radiometer (1%) and the fluctuations of

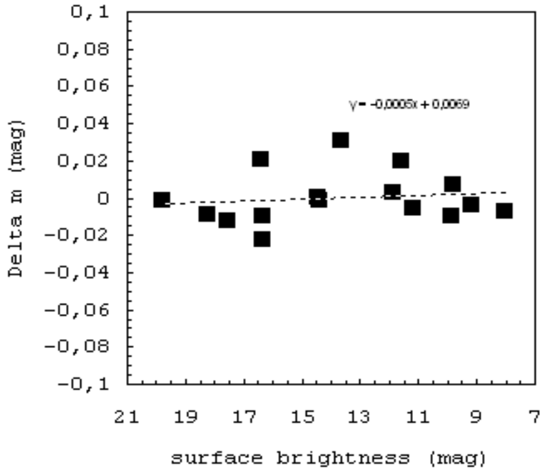

Fig. 6.— Residuals of the comparison of the SQM with a reference radiometer over a variable low-light calibration standard. They give an upper limit to linearity.

the subtracted background. I did not check effects of temperature on linearity but according to the manufacturer the detector is temperature compensated for the ultraviolet-to-visible range from 320 nm to 700 nm (TAOS 2004).

4. Spectral response

I obtained the response curve of our SQM multiplying the spectral responsivity of the TAOS TSL237 photodiode by the transmittance of the Hoya CM-500 filter, both provided by manufacturers, and renormalizing to the maximum value. Fig. 7 shows the normalized photodiode spectral responsivity (solid line) and quantum efficiency (dashed line). The responsivity (response per unit energy) is not flat like the quantum efficiency (response per photon) because photons at smaller wavelength have more energy. Fig. 8 shows the SQM normalized spectral responsivity (solid line), its normalized quantum efficiency and the Hoya filter transmittance (dotted line).

I checked the calculated SQM responsivity with LPLAB's Low-Light-Level Spectral Responsivity Calibration Standard (Cinzano 2003c). The equipment is composed by a standard lamp (lamp 3) powered by an high-accuracy Optronic OL-65-A radiometric power supply (source stability ±0.05%), a collector lens which collect the light on the entrance slit of a Fastie-Ebert monocromator (wavelength accuracy ± 0.2%). A camera lens focuses on the detectors the light coming from the output slit. At the moment at LPLAB we are mainly interested in checking the spectral response of our instruments rather than to obtain accurate responsivity calibrations, so we use a reference detector with known response rather than a certified spectral responsivity standard. The reference detector was a Macam SD222-33 silicon photodiode. Background stray light has been subtracted. Room temperature was maintained at 23±0.5 C.

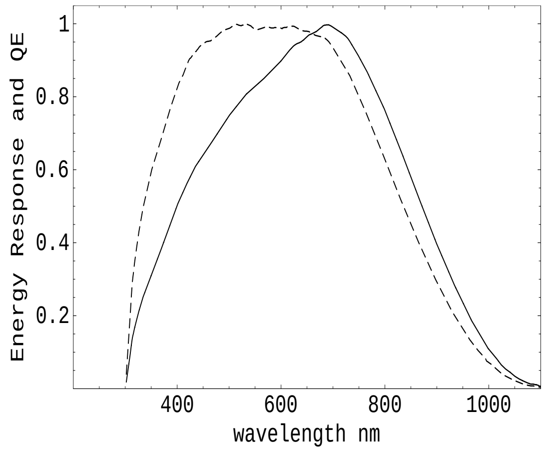

Fig. 7.— Normalized photodiode spectral responsivity (solid line) and quantum efficiency (dashed line).

Fig. 9 shows the measured responsivity of the SQM (squares) compared with its calculated responsivity (line). The measurements follow the calculated responsivity quite well. The reason of the difference over 550 nm is unknown, but main factors could be an inclination of the filter in respect to the incoming light, a different laboratory temperature, an uncertainty in the reference radiometer responsivity. Due mainly to light absorption from collector and camera lenses, the specific irradiance produced on the detector from the Low Light Level Responsivity Calibration Standard become low under about 400 nm, as shown in fig. 10. As a consequence, measurement errors due to the residual background stray light become large at

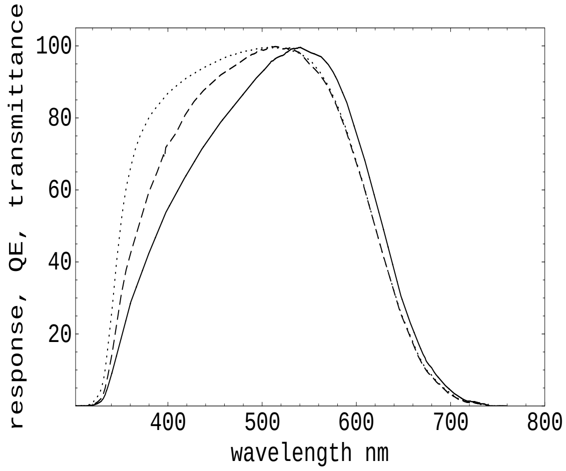

Fig. 8.— SQM normalized spectral responsivity (solid line), quantum efficiency (dashed line) and filter transmittance (dotted line).

these wavelengths.

I checked changes in SQM spectral responsivity due to the inclination of the incoming rays in respect to the normal to the filter. For inclined rays with off-normal angle of incidence θ, the normalized filter transmittance is:

$$T_\lambda = (T_{\lambda,\perp})^{t_\theta/t_\perp} \ , \tag{2}$$

where t_θ is the effective filter thickness:

$$t_\theta = \frac{1}{\sqrt{1 - \frac{\sin^2\theta}{n^2}}} \, t_\perp . \tag{3}$$

I assumed the index of refraction of the glass n=1.55. The Full Width Half Maximum (FWHM) of the normalized transmittance $T_\lambda(\theta)$ decreases with the angle of incidence and, consequently, the same behavior is followed by the normalized spectral responsivity $R_\lambda(\theta) = S_\lambda T_\lambda(\theta)$, where S_λ is the photodiode response. Due to the large field of view, the SQM collects light rays with a wide range of incidence angles. The effective spectral responsivity $\overline{R_\lambda}$ is the average of the spectral responsivity for each incidence angle $R_\lambda(\theta)$ weighted by the angular response $D(\theta)$ given in fig.3 and by the angular distribution of the spectral radiance of the night sky in the field of view $I_\lambda(\theta,\phi)$:

$$\overline{R_\lambda} = \frac{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} R_\lambda(\theta) I_\lambda(\theta,\phi) D(\theta) \sin\theta \, d\theta \, d\phi}{\int_0^{2\pi}\int_0^{\frac{\pi}{2}} I_\lambda(\theta,\phi) D(\theta) \sin\theta \, d\theta \, d\phi} . \tag{4}$$

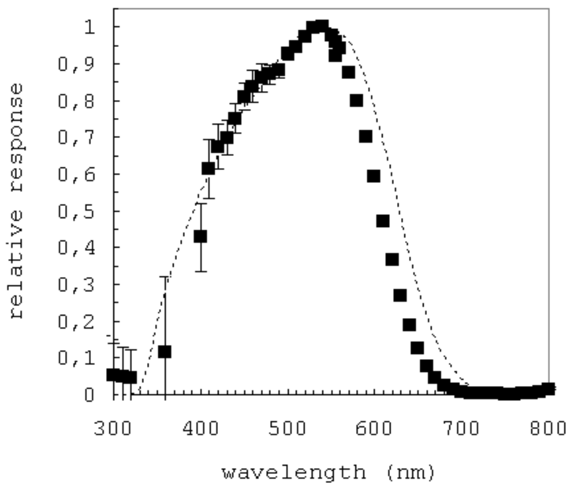

Fig. 9.— Measured SQM responsivity (squares) and calculated SQM responsivity (line).

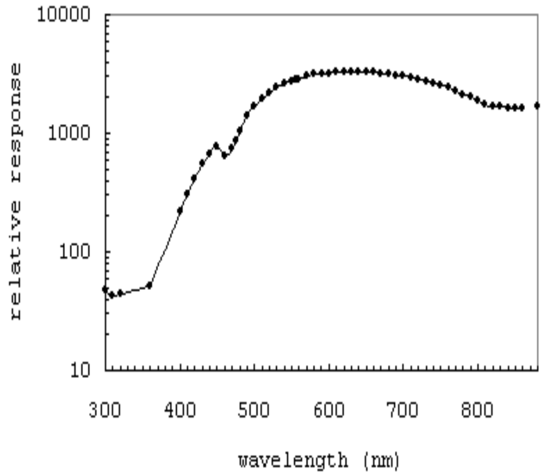

Fig. 10.— Response of the LPLAB's Low-Light-Level Spectral Responsivity Calibration Standard.

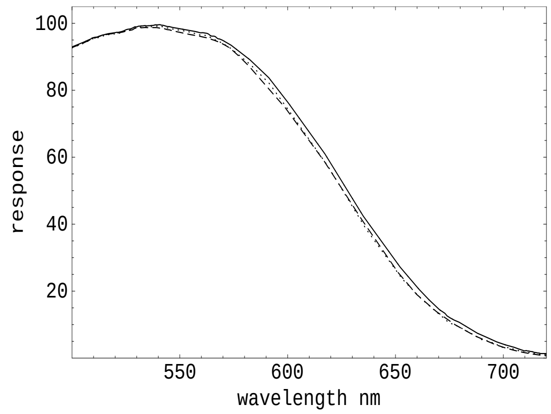

Fig. 11.— Average spectral responsivity of the SQM for an uniform night sky brightness (dashed line), for light rays with 30 degrees incidence angle (dotted line) and for normal incidence (solid line)

Fig. 11 shows the average responsivity of the SQM for an uniform night sky brightness (dashed line), for rays with 30 degrees incidence angle (dotted line) and for normal incidence (solid line). The SQM could slightly underestimate the brightness of the sky when it is polluted from sources with primary emission lines in correspondence of the right wing of the spectral responsivity, where the response is lower. However usual nighttime lighting lamps distribute their energy on many lines, apart from Low Pressure Sodium (LPS) lamps which, anyway, emit near the maximum of SQM response.

5. Relationship between SQM photometric band and V-band

Fig. 12 shows for comparison the SQM normalized response (dotted line) and the standard normalized responses of Johnson's B band, CIE scotopic, Johnson's V band and CIE photopic (dashed lines from left to right). These are some of the main photometric bands used in light pollution photometry. The emission spectra of an HPL mercury vapour lamp (solid line) is also shown. Fig. 13 shows the same responses and the spectra of an HPS High Pressure Sodium lamp (solid line). It is evident that the SQM response is quite different from these standard responses. SQM response is also quite different from the old-time visual and photovisual bands and from the combination of scotopic and photopic eye responses. Its large range recall the sensitivity of panchromatic films. These differences cannot be easily corrected with simple color corrections like in stellar photometry, where sources have nearly blackbody spectra. In facts, spectra of artificial night sky brightness typically have strong emission lines or bands, so small differences in the wings of the response curve can produce large errors.

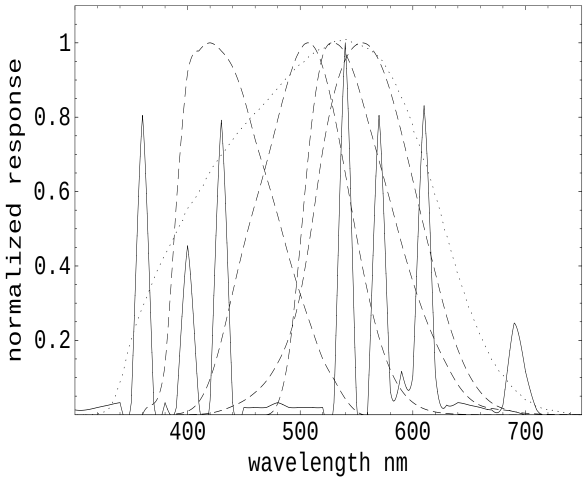

Fig. 12.— SQM normalized response (dotted line), standard normalized responses of Johnson's B band, CIE scotopic, Johnson's V band and CIE photopic (dashed lines from left to right) and emission spectra of an HPL mercury vapour lamp (solid line).

In order to avoid mistakes, it is more correct considering the SQM response as a new photometric system. It adds to the 226 known astronomical photometrical systems listed in the Asiago Database on Photometric Systems (ADPS)(Moro & Munari 2000, Fiorucci & Munari 2003). The conversion factors between SQM photometric system and other photometrical systems can be obtained based on the kind of spectra of the observed object. Hereafter I will call "SQM" the brightness in mag arcsec^{-2} measured in the SQM passband.

The conversion between an instrument response and a given standard response can be made multiplying the instrumental measurement by the conversion factor F_C between the light fluxes collected by the standard response and by the instrumental

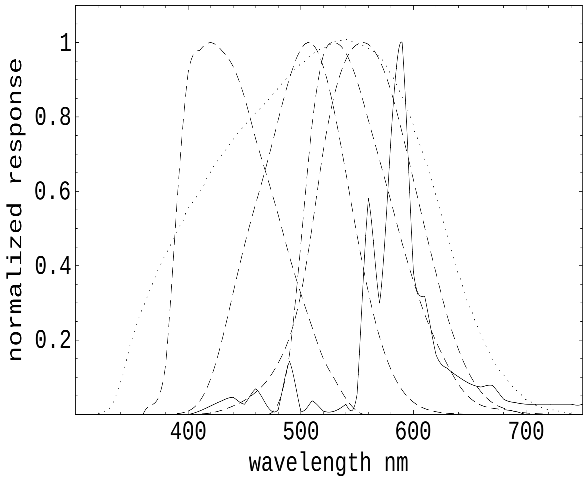

Fig. 13.— SQM normalized response (dotted line), standard normalized responses of Johnson's B band, CIE scotopic, Johnson's V band and CIE photopic (dashed lines from left to right) and emission spectra of an HPS High Pressure Sodium lamp (solid line).

response:

$$F_C = \frac{\int f_\lambda R_\lambda d\lambda}{\int f_{st,\lambda} R_\lambda d\lambda} \frac{\int f_{st,\lambda} S_\lambda d\lambda}{\int f_\lambda S_\lambda d\lambda} , \quad (5)$$

where f_λ is the spectral distribution of the observed object, R_λ is the considered standard response, S_λ is the instrumental response and $f_{st,\lambda}$ is the spectral distribution of the primary standard source for calibration, e.g. an A0V star for the UBV photometric system or Illuminant A for the CIE photometric system. The error due to an uncorrected spectral mismatch is:

$$\varepsilon = \frac{1 - F_C}{F_C} . \quad (6)$$

I computed the conversion factors F_C between SQM response and V band response for: (i) a flat spectrum, (ii) an average moon spectrum obtained assuming the lunar reflectance as given by the Apollo 16 soil and a solar spectral irradiance spectrum from the WCRP model (see Cinzano 2004 for details), (iii) a natural night sky spectrum from Patat (2003) kindly provided by the author, (iv) an averagely polluted sky spectrum obtained with a mix of spectra of natural night sky, High Pressure Sodium (HPS) lamps and HPL Mercury lamps (Cinzano 2004), (v) the CIE Illuminant A (Planckian radiation at 2856 K), (vi) spectra of HPS lamp and HPL lamp taken with WASBAM (Cinzano 2002) and (vii) a series of blackbody spectra at various temperatures. I adopted as the standard response curve of Johnson's (1953) BV bands those given by Bessel (1990, tab. 2), a slightly modified version of the responses given by Azusienis & Straizys (1969).

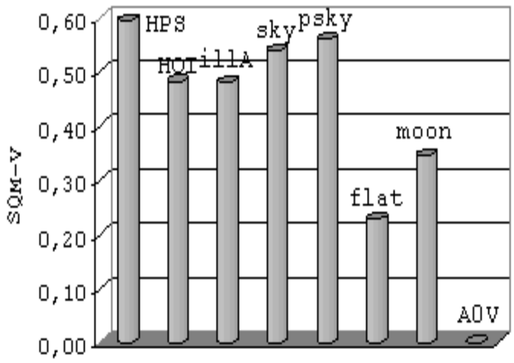

Fig. 14.— Conversion factors from SQM response to Johnson's V band.

The conversion factors from SQM response to Johnson's V band in magnitudes are shown in fig. 14 (see also tab. 2, column 1):

$$SQM - V = -2.5 \log_{10} F_C \quad (7)$$

Here I will continue to call them conversion "factors" even if SQM-V is an addictive constant. I assumed here that both bands are calibrated over a primary standard AOV star spectra like alpha Lyrae. As absolute calibrated spectrum I adopted a synthetic spectrum of alpha Lyrae from Kurucz scaled to the flux density of alpha Lyrae at 555.6 nm given by Megessier (1995), as discussed in detail by Cinzano (2004).

The conversion factors are large, as expected because of the large difference in the response curves. However, given that the SQM will be used to measure light pollution and it will never be used to measure stars or sources with flat spectra, the conversion factors for interesting sources lie in the narrower range 0.35-0.6 mag arcsec^{-2}. They can be reduced using a calibration source inside the

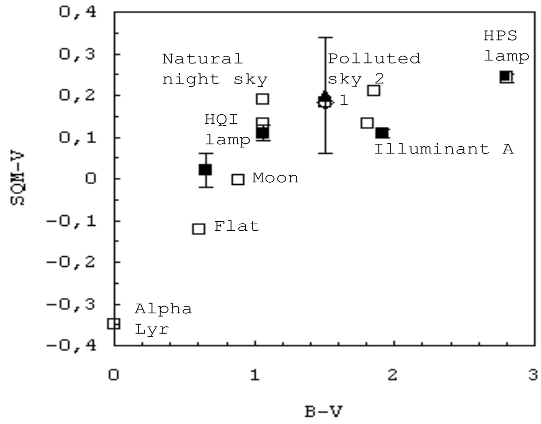

Fig. 15.— SQM-V measured ■ and calculated □.

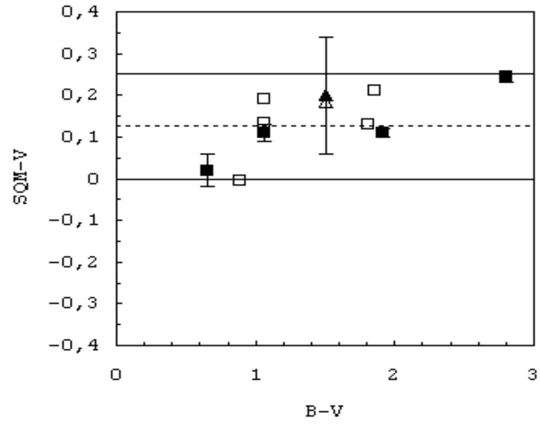

Fig. 17.— Limited range of interesting SQM-V.

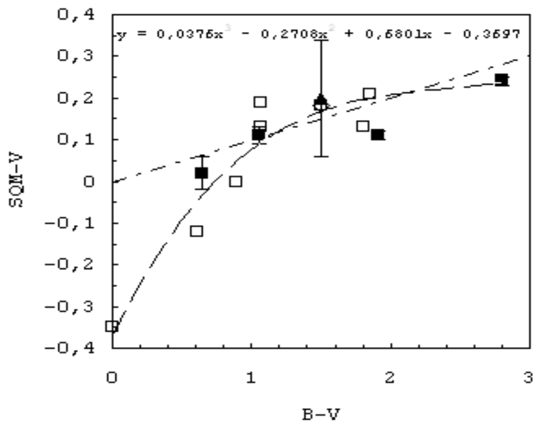

Fig. 16.— SQM-V versus B-V is not linear.

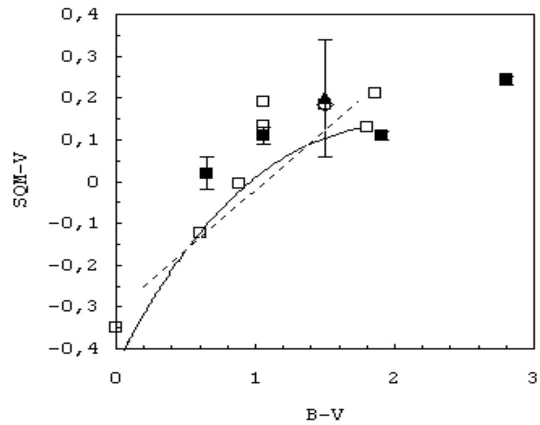

Fig. 18.— SQM-V for blackbodies (solid line).

same range, like Illuminant A or another lamp for nighttime lighting. As an example, referring them to an Illuminant A lamp (SQM-V=0.48 mag arcsec^{-2}) these conversion factors would lie in the range ± 0.12 mag arcsec^{-2}. In fact Unihedron uses for calibration a fluorescent lamp (their zero point will be discussed later). The argument is further faced in the following discussion.

I measured the SQM-V conversion factors for a number of sources by comparing SQM measurements with V-band measurements made with the IL1700 research radiometer (accuracy of V band calibration $\pm 4.9\%$, linearity 1%). Fig. 19 shows the equipment used for some measurements. Fig. 15 shows the measured (filled squares) and calculated (open squares) conversion factors from SQM response to the V band in magnitudes per square arcsec in function of the B-V color index of the source. I shifted the zero-point of calculated factors to approximately fit the corresponding measured ones. Fig. 16 shows that the sources do not follow a simple B-V relation, as expected. Even if a polynomial (dashed line) could give a very rough fit to datapoints, a SQM-V versus B-V relation does not make sense because data points depend on the spectra of the source which in general is not univocally determined by the color index. Except few cases, lamps for nighttime lighting are discharge lamps or LEDs, which are very different from blackbodies. Fig. 17 shows that if we consider only sources related to light pollution, conversion factors lie in the range 0-0.25 mag arcsec^{-2}. As already pointed out, using an higher zero-point or using an Illuminant A calibration source, the range could be restricted to about ± 0.12 mag arcsec^{-2}.

Fig. 18 shows the SQM-V versus B-V relationship for blackbodies (solid line). As expected, it fits Illuminant A, the Moon, a flat spectra and alpha lyrae. The last is not fitted well because a A0V star spectra it is not a true blackbody due to absorption lines and bands. A polynomial interpolation gives $SQM–V = -0.162(B–V)^2+0.599(B–V) - 0.426$. Linear regression gives $SQM - V \approx 0.25(B - V) - 0.26$ when based on datapoints regularly distributed within $0.4 \leq B - V \leq 1.7$ and $SQM–V \approx 0.28(B–V)–0.30$ when based on datapoints within $0.5 \leq B - V \leq 1.7$.

Two independent authors tested the SQM at the telescope over standard stars finding a good agreement with $SQM - V' \approx 0.2(B' - V')$ (Unihedron, priv. comm.). The smaller angular coefficient could be explained by the differences between stellar and blackbody spectra, i.e. by the different distribution of stellar datapoints in respect to blackbody datapoints on the plane SQM-V versus B-V. The different zero point is likely due to the fact that the relation has been obtained with outside-the-atmosphere magnitudes V' and B'. As an example, assuming an extinction of 0.35 mag in V and 0.15 mag in B and replacing V'=V-0.35 and B'=B-0.15, where V and B are the apparent magnitude below the atmosphere, we obtain $SQM - V = 0.2(B - V) - 0.31$ in agreement with my previous results. The zero point of the current SQM calibration made by Unihedron gives SQM≈V' for stars with B'=V', above the atmosphere, and consequently the below-the-atmosphere SQM-V correction factor for the alpha Lyrae spectrum come out different from zero. Fig. 18 shows that for alpha Lyr is SQM-V=-0.35 mag arcsec^{-2}.

Given that the instrument is not used for measurements of stars at the telescope, this feature appears not necessary. On the contrary, by referring the calibration to an Illuminant A and the zero point to the condition SQM=V (below the atmosphere), the conversion factors for the sources related to light pollution would have been reduced to the range $\approx \pm 0.12$ mag arcsec^{-2}. My best calibration to Illuminant A, obtained with the LPLAB Low Light Level Calibration Standard, the spectral radiance standard lamp no. 7 powered by the LCRT-2000 radiometric power supply (radiance stability 1% at 550 nm) and the IL1700 reference radiometer (accuracy of V band calibration ±4.9%, linearity 1%), provides $V = SQM - 0,108 \pm 0.054$ mag arcsec^{-2}. The errorbar includes both the measurement uncertainty and the V band calibration uncertainty of the reference photometer. The condition SQM$_{new}$=V for Illuminant A is satisfied increasing the current SQM zero point of 0.108 mag arcsec^{-2} or subtracting this number from current measurements. Given the many uncertainty factors playing when comparing instruments, before an official change of zero point a wider comparison should be carried, better if also including measurements over the night sky. The SQM-V conversion factors after the adjustment are listed here:

Fig. 19.— The Variable Low Light Level Calibration Standard. From left to right are visible the SQM and the reference detector, the Uniform Integrating Sphere, the aperture wheel and a test lamp for road lighting (baffles removed). Spectral irradiance/radiance standard lamps with radiometric power supplies and optical devices are used in other configurations.

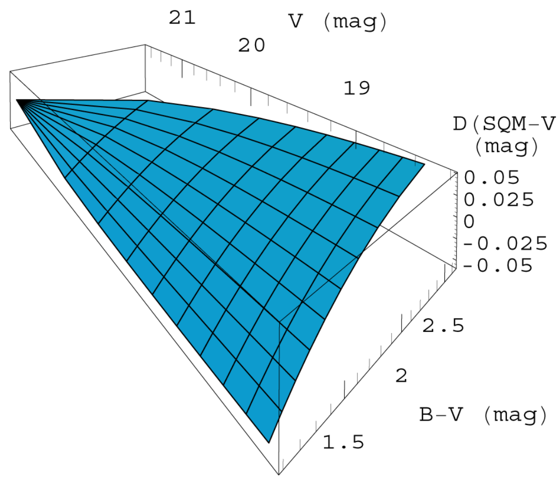

Fig. 20.— SQM-V conversion factor (mag arcsec^{-2}) for a night sky model spectrum, in function of its V brightness and B-V color index.

source	SQM-V
HPS lamp	+0.11
HPL lamp	+0.00
illuminant A	+0.00
sky natural	+0.06
sky polluted	+0.08
moon ab. atm.	-0.13

I finally explored the relation between the conversion factor SQM-V for the night sky spectrum and its V brightness and B-V color index. Following Cinzano (2004), I constructed a very simple model spectra for polluted sky assuming that the night sky brightness spectrum f_{sky} is given by the sum of a natural night sky spectrum, an HPS lamp spectrum and an HPL mercury vapour lamp spectrum, each of them multiplied by a coefficient k_n, independent by the wavelength:

$$f_{sky} = f_{nat} + k_1 \left(k_2 f_{HPS} + (1 - k_2) f_{HPL}\right) \quad (8)$$

With this spectrum I calculated the function $SQM - V\,(V_{sky}, (B - V)_{sky})$. Fig. 20 shows the conversion factor SQM-V of the night sky in magnitudes per square arc second in function of the V brightness and the B-V color index. The conversion factor is referred to the natural sky, i.e. its adds to the SQM-V of the natural sky (+0.48 mag arcsec^{-2} if calibration refers to alpha Lyr or +0.06 mag arcsec^{-2} if calibration refers to Illuminant A).

6. Addition of filters for CIE photopic, CIE scotopic, V-band, B-band

I also calculated with eq. 5 the spectral mismatch correction factors between SQM response and the CIE photopic, CIE scotopic, V-band, B-band responses, when specific filters are added. I considered addition of filters rather than replacement of the existing filter because more on line with the SQM philosophy of simple and fast measurements. Anyone can add a filter in front of the instrument whereas replacement requires specific work. Calculations assume that the instrument is properly calibrated over an Illuminant A for the CIE photometric system and over an AOV star, like alpha Lyrae, for Johnson's B and V (or properly rescaled to it). I choose for these tests an Optec Bessell V filter, an Optec Bessell B filter, an Oriel G28V photopic filter and a scotopic filter.

Fig. 21 shows the standard response (solid line) and the SQM+filter response (dashed line) for CIE photopic (top) and CIE scotopic responses (bottom). The SQM response is also shown for comparison (dotted line). The spectral mismatch correction factors for the photopic and scotopic responses are presented in tab. 1. The standard responses of the CIE photometric system are given in CIE DS010.2/E where they are called "spectral luminosity efficiency functions". The instrument is assumed to have been calibrated over an Illuminant A spectrum. Tab. 1 shows that after the application of the filter the spectral mismatch correction factors became quite small, so that correction could be neglected. The match to the CIE photopic response could be further improved choosing a filter with the left wing at larger wavelengths. The match of scotopic response is adequate.

Fig. 22 shows the standard response (solid line) and the SQM+filter response (dashed line) for V band (top) and B band (bottom). The SQM response is also shown for comparison (dotted line). The spectral mismatch correction factors in magnitudes per square arcsec for the Johnson's B and V bands are presented in tab. 2. The instrument is assumed to have been calibrated over an AOV star spectra, like alpha Lyrae, or properly rescaled to it. The match of V band response is adequate. The match to the B band could be further improved choosing a filter with the left wing at lower

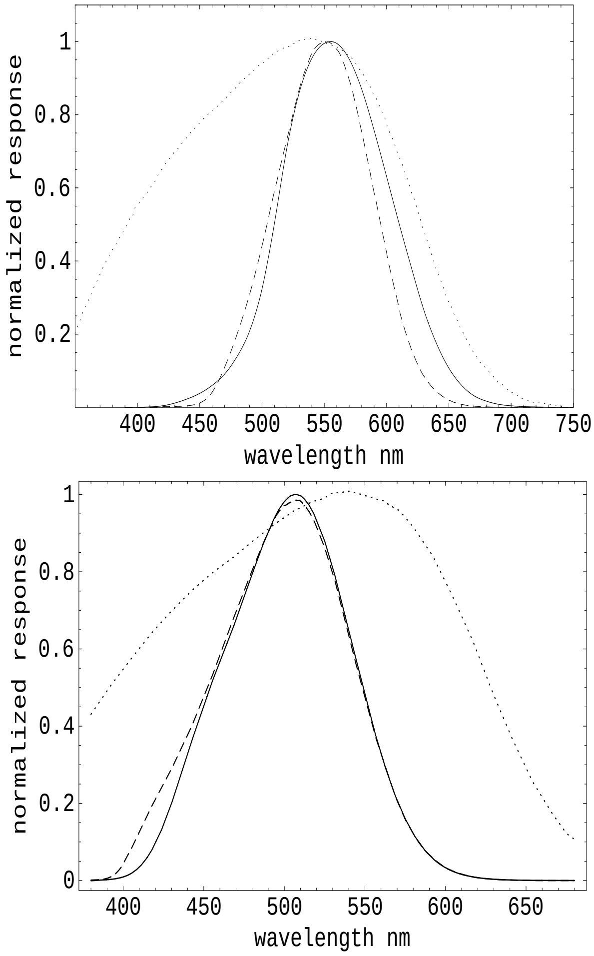

Fig. 21.— Top panel: CIE photopic response (solid line) and SQM + G28V filter (dashed line). Bottom panel: CIE scotopic response (solid line) and SQM + scotopic filter (dashed line).

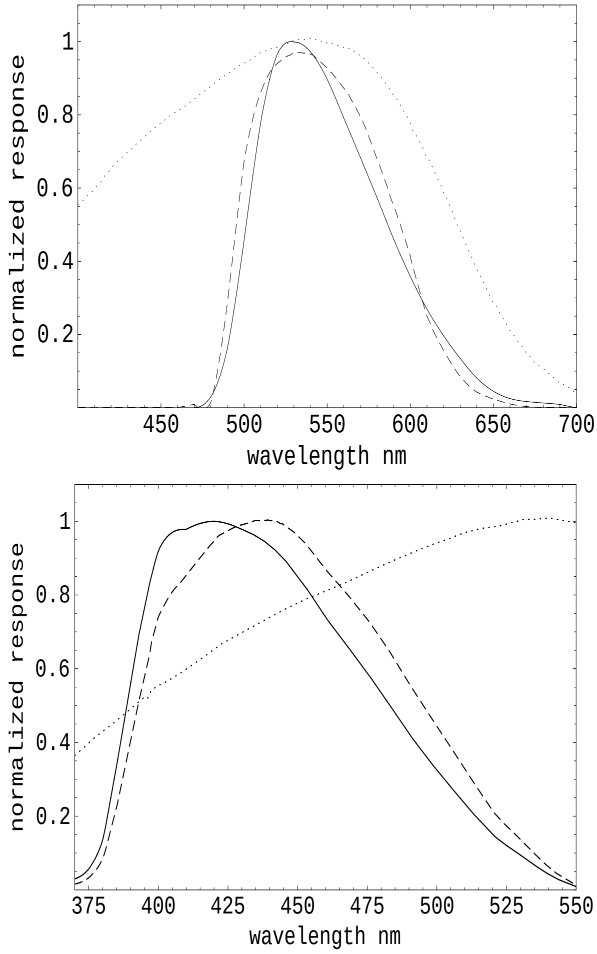

Fig. 22.— Top panel: V band response (solid line) and the SQM+ Optec V filter (dashed line). Bottom panel: B band response (solid line) and the SQM+ Optec B filter (dashed line).

wavelengths.

7. Further notes on measurement comparison

When comparing SQM measurements with measurements made with other instruments, it should be taken also into account that:
a) SQM, like the other photometers, radiometers, luminancemeters and WASBAM, correctly measures the night sky brightness "below the atmosphere", the way it was. On the contrary, measurements made with instruments applied to telescopes are "below the atmosphere" when the calibration factor and extinction are properly evaluated with the Bouguer method but are wrongly given as "above the atmosphere" when counts from standard stars and sky background are compared without accounting for extinction from the top of the atmosphere to the ground.
b) SQM includes all stars whereas measurements of sky background made with telescopes usually exclude field stars more luminous than a given magnitude. When the artificial brightness is not predominant, the contribution of these stars to the night sky brightness should be added before comparing telescopical measurements with SQM measurements (table 3.1 of Cinzano 1997 could be

source	Photopic		Scotopic	
	no filter	filter	no filter	filter
HPS lamp	0,78	1,01	1,70	1,00
HPL lamp	1,02	1,06	1,22	1,06
illuminant A	1,00	1,00	1,00	1,00
sky natural	0,96	1,05	0,79	1,02
sky polluted	0,85	1,02	1,37	1,02
moon ab. atm.	1,20	1,08	0,79	1,02
flat	1,35	1,08	0,84	1,03

Table 1: Spectral mismatch correction factors for CIE photopic and scotopic responses.

source	V band		B band	
	no filter	filter	no filter	filter
HPS lamp	+0,59	-0,05	-2,26	+0,10
HPL lamp	+0,48	+0,04	-0,63	-0,01
illuminant A	+0,48	+0,04	-1,37	+0,20
sky natural	+0,54	+0,02	-0,57	+0,04
sky polluted	+0,56	-0,02	-1,34	+0,03
moon ab. atm.	+0,35	+0,01	-0,59	+0,07
flat	+0,23	+0,01	-0,43	+0,02
alpha Lyrae	+0,00	+0,00	+0,00	+0,00

Table 2: Spectral mismatch correction factors for V and B responses in magnitude per square arcsec.

used). When the night sky brightness is referred to naked eye, only stars to magnitude 6 should be included. However the contribution of stars more luminous of mag 5 (included) is only 6% of the natural night sky brightness.

8. Conclusions

Sky Quality Meter is a fine and interesting night sky brightness photometer. Its low cost and pocket size allow to the general public to quantify the quality of the night sky. In order to understand the measurements made by it, I checked acceptance angle, linearity and spectral responsivity. I analyzed the conversion between SQM photometric system and Johnson's B and V bands, CIE photopic and CIE scotopic responses and determined for some typical spectra both the conversion factors and the spectral mismatch correction factors when specific filters are added.

Comparing SQM measurements with measurements taken with other instruments it should be taken into account that:

a) conversion factors from SQM photometric system to Johnson's V band are in the range 0-0.25 mag arcsec^{-2} when considering only main sources of interest for light pollution. They are presented in fig. 15.
b) conversion factors for the polluted sky differs from the factor for the natural sky less than ± 0.05 mag arcsec^{-2} and can be related to the sky V brightness and B-V color index (fig. 20).
c) quick conversion factors to obtain V band brightness from SQM measured brightness with current factory calibration are proposed here below for further testing. They are chosen to minimize the expected uncertainty ΔV.

Conversion for	V	ΔV
Natural & polluted sky	SQM-0.17	±0.07
Lamps, sky, moonlight	SQM-0.11	±0.14

First line is for typical natural or polluted sky, the second line is for surfaces lighted by artificial sources (HPS, HPL, Illuminant A), natural night sky, polluted night sky or moonlight. The uncertainty of the V band calibration of the reference photometer used in test measurements is included in ΔV. Units are V mag/arcsec^2.
d) SQM gives the average night sky brightness, weighted for the angular response inside an acceptance area which has a diameter of 55 degrees down to 1/10 attenuation. Due to the gradients of the night sky brightness with zenith distance, the SQM average brightness is larger (smaller mag arcsec^{-2}) than the brightness measured by a narrow field photometer pointed in the same direction, as shown e.g. in fig. 5. In order to roughly estimate the punctual V band brightness, add to SQM measurements 0 to 0.3 mag/arcsec^2 at zenith or 0 to 0.4 mag/arcsec^2 at 30 degrees of zenith distance, depending on the pollution level.
e) SQM correctly gives the brightness "below the atmosphere" whereas telescopical measurements calibrated on standard stars give "below the atmosphere" brightness only when the extinction is properly evaluated and accounted for.
f) SQM correctly fully includes the stellar component in the measured brightness whereas telescopical measurements frequently exclude stars more luminous than a given magnitude.
g) addition of commercial Johnson's B band, V band, CIE photopic or CIE scotopic filters in front of the SQM with proper calibrations, makes

the spectral mismatch correction factors very low. This allows reasonably accurate multiband measurements, including B-V color indexes and scotopic to photopic ratios.

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