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A portable spectrophotometer for light pollution measurements

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Abstract. A portable spectrophotometer is presented for monitoring night sky brightness and light pollution emissions in the spectral range from 420 nm to 950 nm. It allows hyperspectral mapping of the night sky at sites and across the territory with compactness, transportability and automatic coverage of a grid of points. Analysis with synthetic photometry provides maps of the night sky brightness in any photometrical band of the visible spectral range and in the "light" of main lamps, with their color indexes. It also allows hyperspectral mapping of landscapes.

Key words. instrumentation: spectrophotometers – light pollution – site testing – night sky brightness

1. Introduction

Light pollution sources frequently have strong emission lines and bands. For this reason spectrophotometry is a more complete method of evaluation of the alteration produced to the night environment than wide band photometry. Spectrophotometry is already an established pratique to evaluate the situation of the night sky in astronomical sites or in urban sites, but its interest is wider. It adds the wavelength dimension to the mapping of the night sky brightness in a site or across a territory, like these introduced by Cinzano, Falchi & Elvidge (2001) and Cinzano & Elvidge (2002). Wavelength dimension carries important information on the propagation of light pollution on the atmosphere, on the emission of pollution sources, on the changes of lighting habits with time and so on. To carry on these kinds of studies, I set up a portable spectrophotometer for light pollution measurements with automatical mapping capabilities at the Laboratory of Photometry and Radiometry of Light Pollution (Cinzano 2003a,b) of Light Pollution Science and Technology Institute (ISTIL/LPLAB).

The basic design goals were: 1) spectral coverage of the visual wavelength range from 400 nm to 1000 nm; 2) lightness, compactness and portability; 3) large field of measurement for fast exposition times; 4) good equilibrium between spectral resolution and fast exposition time; 5) absolute calibration on-site; 6) reasonably quick set-up on-site with limited needs of time-expensive adjustments; 7) possibility of automatic mapping of the entire sky with a series of spectra, with automatic registration of position, elevation, date, time, altazimuthal and equatorial celestial coordinates; 8) automatic data reduction; 9) low cost with

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Fig. 1. The WASBAM-SSH spectrophotometer.

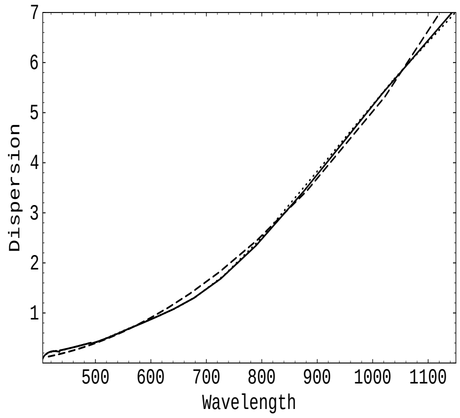

Fig. 2. The dispersion of SSH (nm/px) as obtained from wavelength calibration (solid and dotted line). The best fitting Hartmann function (dashed line) is plotted for comparison.

easy available components and control software. Here I present the instrument, its calibration and data reduction.

2. Description

The spectrophotometer is composed of a cooled CCD camera and a small spectrographic head (SSH). The camera is the same SBIG ST-7E camera used for the Wide Field Sky Brightness Automatic Mapper (WASBAM; Cinzano & Falchi 2003,see fig.1). It carries a Kodak KAF0401E CCD with 760×510 pixels (9×9 μm^2 pixel size) no-antiblooming and a spectral response going from about 430 nm to 830 nm FWHM. The shutter is electromechanical and CCD temperature is controlled with ±1° accuracy by a solid state thermoelectric Peltier cooler.

The small spectrographic head is a Browning direct-vision design with a De Amici prism composed of two external Crown prisms and an inner Flint one. This maintains the size at minimum, so that SSH appears like a small ”telescope” with external size of less than 17 cm of length and 5.5 cm of diameter. It can be quickly exchanged with the WASBAM lens when photometrical measurements are needed. The head carries a lens with Tessar-like optical design and focal length F=30 mm, provided by Costruzioni Ottiche Zen, Venezia. The aperture ratio is $f5$, as determined by the collimator which has a focal length of about F=50 mm. The slit is adjustable, so it can be opened in very dark sites or whenever a faster sky mapping with short exposures is privileged in respect to a better resolution. The bad side is that the slit width could change during the transport. This requires check and radiance calibration before each measurement, which in part mismatches our goal no. 6. The camera lenses focus on the CCD an image of the slit giving a spectrum ranging from 400 nm to 1150 nm in about 750 pixels along the long dimension of the CCD. The dispersion increases from 0.2 nm/px at 400 nm to 7 nm/px at 1150 nm, as shown in fig. 2. The range of interest is from 420 nm to 950 nm where the dispersion ranges from 0.2 nm/px to 4.5 nm/px with 0.6 nm/px at 550 nm. The light is collected from a solid angle of about 0.2°× 3.8° when slit width is 100 μm and 100 rows are binned. The mechanical design allows 8 screw adjusting the head in respect to the camera. The full spectral range is focused tilting the camera in respect to the image plane. The spectrum fills the upper half of the CCD with an adjustable slit height. The other half is intended to be filled by the comparison spectrum. In night sky mapping only average spectra in each direction are

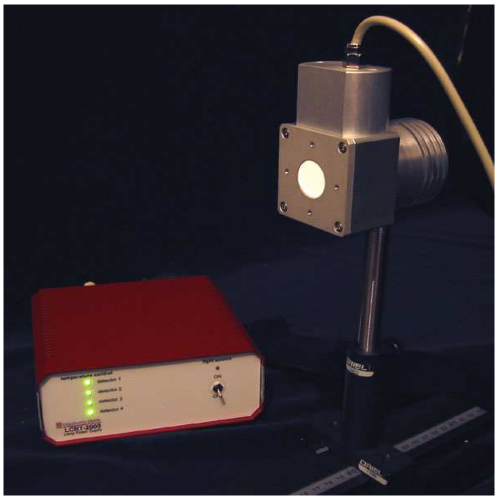

Fig. 3. The Portable Spectral Radiance Standard.

needed. They are obtained binning a range of rows in order to increase the signal to noise ratio and shorten exposure times. The signal to readout noise ratio is ≥3 at 550 nm exposing 40 minutes the unpolluted night sky (≈3.7 10^{-9} W m^{-2} sr^{-1} nm^{-1}) with 100 rows binned and 100 μm slit width.

The spectrophotometer alone (camera+SSH) weights only 1.9 kg. It works on a simple tripod or, like the photometric configuration of WASBAM, on a computerized altazimuthal mount Celestron Nextar 4, through an aluminium adapter made by Officine Marcon, San Donà di Piave, Italy (Cinzano & Falchi 2003). The computerized mount with tripod weights 7.6 kg. The software Orchestrate by Software Bisque automatically controls all the operations of the mount and the CCD camera. The mount set-up procedure (Cinzano 2002) is quite fast, mainly requiring to place the instrument, insert the geographical position obtained with a GPS receiver, tune the alignment with two stars chosen by the instrument and start the Orchestrate procedure. It exposes automatically a sequence of spectra on a grid of points in azimuth and altitude on the sky. A software still under development interpolates the spectra taken toward each grid point of the sky producing an hyperspectral image of the entire night sky. It can be analyzed with synthetic photometry to obtain maps of the night sky brightness distribution at a site or across a territory in any photometrical band of interest for light pollution evaluation in the visual range. It also provides the radiance distribution in the "light" of main lamps (e.g. in "High Pressure Sodium light" and "Mercury Vapours light").

3. Calibration

Wavelength calibration is made with a portable Mercury-Argon wavelength standard lamp StellarNet, USA with a fiber optic cable. Calibration wavelength ranges from 253.65 nm to 1013.98 nm. In practice I found convenient separate comparison spectra with different exposure times, taken before and after the science exposure with the calibration lamp in front of the lens. This also corrects possible distortions.

Spectral radiance calibration is made with a compact and light Portable Spectral Radiance Standard which can be used on-the-field, using a battery inverter. Night sky brightness and other light pollution measurements are made below the atmosphere, so there is no need for spectrophotometrical standards above the atmosphere. In any case, the large field of view and the design of the instrument make awkward using standard stars for calibration. Fig. 3 shows the Spectral Radiance Standard, made by Gigahertz-Optik, Munich. It consists of a 2 inches diameter OP.DI.MA 15/10 integrating sphere with a symmetrical baffle which offers a ≤ 1.5% radiance uniformity at the 20 mm diameter output port. Its QTH tungsten halogen lamp is current controlled by the LCRT radiometric power supply with current accuracy ≤0.25% /K (from 23 ±1°) giving an uncertainty of approximately ≤ ±2.3% at 300 nm, ≤ ±1.0% at 550 nm and ≤ ±0.5% at 1000nm. Spectral radiance calibration range goes from 380 to 1100 nm with a color temperature of 2713 K and a spectral radiance uncertainty relative to NIST ≤ ±6% from 380 to 780 nm and ≤ ±8% from 790 to 1100 nm. The effects of the external temperature should be monitored and corrected for, even if first tests did not show large variations. Typical spectral ra-

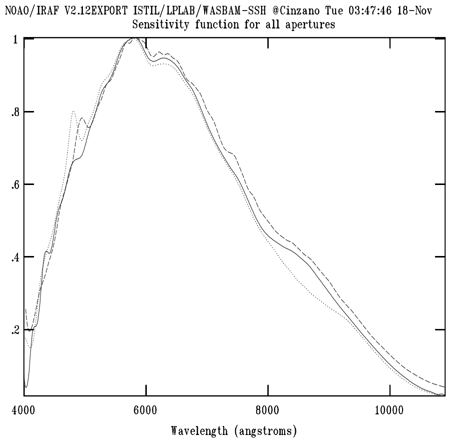

Fig. 4. Sensitivity curves of WASBAM SSH for some choices of line range (solid and dotted line) and a different set-up (dashed line).

diance is 238.9 mW m^{-2} nm^{-1} sr^{-1} at 550 nm. A neutral calibrated filter reduces the radiance to 1/100 increasing exposure times and avoiding shutter errors.

The instrumental sensitivity function is presented in fig. 4. A comparison with the CCD quantum efficiency declared by the manufacturer suggests that the disperser efficiency decreases about 50% from 500 nm to 900 nm. On the other side, it falls rapidly down between 500 nm to 400 nm due to glass absorption. The sensitivity function should be obtained binning the same range of rows which will be used to bin the final spectra. The sensitivity at 580 nm is roughly 10^5-10^6 counts s^{-1}/ W m^{-2} sr^{-1}, depending on slit width and binning. At the moment, the accuracy is $\pm$10% in the range from 420 nm to 950 nm but it is expected to improve substantially going on with tests.

4. Data reduction and analysis

The data reduction is made with imred package in IRAF (Cinzano 2003c). The uniform diffuse background due to stray light is subtracted fitting a polynomial to CCD rows outside the spectra. I plan to subtract reflections independent from wavelength and stray light disuniformities mapping their relative intensity on exposures of monochromatic sources.

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