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# MEASURING THE NIGHT SKY BRIGHTNESS WITH THE LIGHTMETER

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RESUMEN

Se presenta un fotómetro de bajo costo, recientemente desarrollado, para el monitoreo de largo plazo de la luminosidad del cielo nocturno y la contaminación lumínica terrestre. El Medidor de Luz es en la medida de lo posible operacionalmente autónomo, completamente a prueba de agua y no necesita mantenimiento. Este provee de una tasa de muestreo alta de hasta 1 Hz así como también de una magnífica sensibilidad y cubre el rango completo de luminosidad hasta las condiciones de noche más oscuras. El excelente desempeño del Medidor de Luz permite monitorear continuamente la luminosidad del cielo nocturno y abre un rango amplio de aplicaciones para un observatorio como la determinación de las condiciones de todo el cielo en tiempo real, la detección de nubes y estimación de sus velocidades, midiendo los cambios relativos en la extinción atmosférica, así como la detección de tendencias a largo plazo de la luminosidad causadas por el aumento de la iluminación artificial. Se presentan los primeros resultados de las mediciones en Cerro Armazones, uno de los mejores sitios de observación en el mundo y el sitio seleccionado para el European Extremely Large Telescope (E-ELT).

ABSTRACT

We present a newly developed, low-cost photometer for long-term monitoring of the night sky brightness and light pollution on Earth. The so-called LIGHTMETER is an as far as possible stand-alone operational, fully weatherproof, and maintenance-free device. It provides a high data sampling rate of up to 1 Hz as well as a superb sensitivity covering the whole brightness range down to the darkest night time conditions. The excellent performance of the LIGHTMETER allows a continuously monitoring of the night sky brightness and opens a wide range of applications at an observatory site like determining overall sky conditions in real time, cloud detection and estimation of their velocity, measuring relative changes in extinction as well as the detection of long term trends in brightness caused by an increase of artificial illumination. We will present first results of measurements taken at Cerro Armazones, one of the best observing sites in the world and the selected site of the planned European Extremely Large Telescope (E-ELT).

*Key Words:* instrumentation: photometers — light pollution — methods: data analysis — methods: observational — site testing



## 1. INTRODUCTION

Monitoring the brightness of the night sky is usually an elaborate and expensive task. The operation of complex all-sky cameras and telescope systems make continuous measurements at any time and weather condition impossible. In addition, these systems come along with a complex infrastructure like buildings in order to protect the sensitive hardware against weather and solar illumination. We present a newly developed photometer, which we call LIGHTMETER in the following. The LIGHTMETER consists of a photo voltaic cell, electronic components like amplifier and A/D converter, which are implemented in an aluminum frame and can be connected to any computer using USB (Figure 1).

Fig. 1. The LIGHTMETER device.

In order to be able to integrate over the full hemisphere of the sky, the LIGHTMETER has to be assembled parallel to the horizon, preferable above any structure to avoid dome shadowing and direct il-

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lumination by artificial light sources. The LIGHTMETER is fully weatherproof, maintenance-free, operates during the whole year, and is sensitive down to the darkest night time conditions. Thus, it is the perfect device to establish a large network all over the planet in order to detect changes and measure long-term trends in the night sky brightness caused by growing cities and industry (light pollution). In addition, the data of LIGHTMETER can support site selection processes and operation of astronomical observing facilities (§ 3).

## 2. OBSERVATION AND DATA REDUCTION

We present a first set of measurements taken at Cerro Armazones in Chile, the site of the future E-ELT. The data set covers 107 days, starting from January 28th, 2010 to May 14th, 2010. The LIGHTMETER was mounted next to the platform of the DIMM tower (differential image motion monitor, Sarazin & Roddier 1990) and was operated with a data sampling rate of 1 Hz. A text file is produced as output, containing date, time, measured raw counts, and temperature from an internal temperature sensor.

In order to be able to measure over the whole natural brightness range, the LIGHTMETER has a non-linear behavior. By construction non-linearity typically starts at full moon brightness, with a percent level departure from a linear relation, say. That maximizes the linear range available for dark-sky measurements. In addition, the sensitivity of the sensor can degrade with time and its sensitivity is temperature dependent. To account for these variable effects we are using the Sun and the Moon as natural calibrator sources.

To reduce the huge amount of data (86 400 measurements per day), we are using a pipeline written in the Interactive Data Language (IDL). The pipeline performs several steps which are summarized in the following:

- sorting the data for each day (one day is equal to one Julian day)
- detection of clouds by computing a running root mean square (RMS)
- computation of Lunar and Solar ephemerids
- computation of the theoretical Lunar irradiance by using a disk-equivalent reflectance model by Kieffer & Stone (2005) and ASTM E490 Air Mass Zero solar spectral irradiance data (ASTM E490)[4]
- computation of the theoretical Solar irradiance by using ASTM E490
- for the computation of the airmass the model by Rozenberg (1966)
- for the computation of the extinction caused by atmosphere of the Earth the model by Hayes & Latham (1975) is used
- the spectral response of the LIGHTMETER is taken into account
- simultaneous fit of the LIGHTMETER raw counts to the computed irradiance model (Sun and Moon), only parts without clouds and altitudes $\geq +20°$ of Sun and Moon are considered

The fit of the data to the irradiance model is done using following expression:

$$\begin{aligned} l &= c \cdot cnt \cdot (1 + d \cdot T)\,, \\ &+ c \cdot \left\{ b \cdot \left[ a \cdot \exp\left( \frac{cnt \cdot (1 + d \cdot T)}{a} \right) - 1 \right] \right\}\,, \end{aligned} \tag{1}$$

where $I$ is the measured irradiance by the LIGHTMETER, $a$, $b$, $c$, and $d$ are the fit parameters, $T$ is the measured temperature of the LIGHTMETER, and $cnt$ are the measured raw counts. This expression accounts for the non-linearity behavior as well as the temperature dependent sensitivity of the LIGHTMETER. This fit is carried out on a daily basis using following constraints:

- the altitude of Sun and Moon have to be $\geq +20°$
- sky conditions have to be clear

Therefore, we directly account for degradation effects in sensitivity of the device, too. The upper plot of Figure 2 shows an example of the fit of LIGHTMETER measurements to the computed irradiance model for March 29th, 2010 (no clouds were present, night with full moon). Measurements that are not considered for the fit are not plotted (e.g. twilight, low altitudes of Sun and Moon). The lower plot of Figure 2 shows the relative RMS of the fit between the irradiance model and the measured data. The scatter in the relative RMS around noon (15 to 18 p.m. UT) is caused by the heating of the LIGHTMETER due to solar radiation. The temperature of the sensor easily reaches 50°C during noon at Cerro Armazones and equation 1 does not account for additional side-effects of the sensor that might occur during this time.

The pipeline produces several files as output. A daily night log is produced containing the main measurements of the night: date, length of the night, illuminated fraction of the moon, JD, time stamps in UT, Irradiance, data of the running RMS (cloud detection), temperature of the sensor, and altitude of the moon. The fit parameters are written into a

[4] `http://rredc.nrel.gov/solar/spectra/am0`.

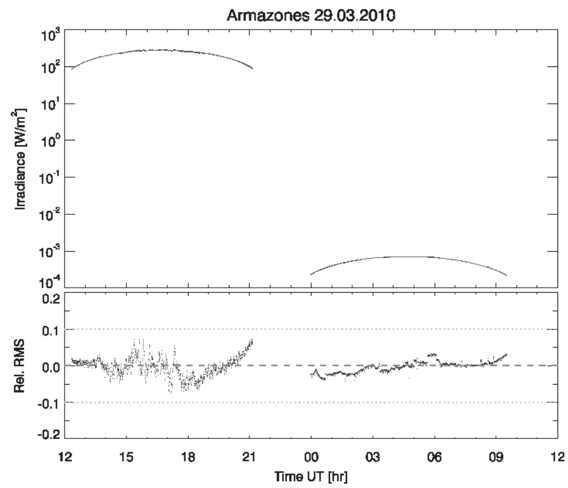


Fig. 2. Example of a fit of the measured LIGHTMETER data to the irradiance model for March 29th, 2010 (no clouds were present, night with full moon). The relative RMS (lower plot) of the fit between the measured data and the irradiance model inside the range of 10%. Because of the good fit performance the measured data are not distinguishable from the computed irradiance model.

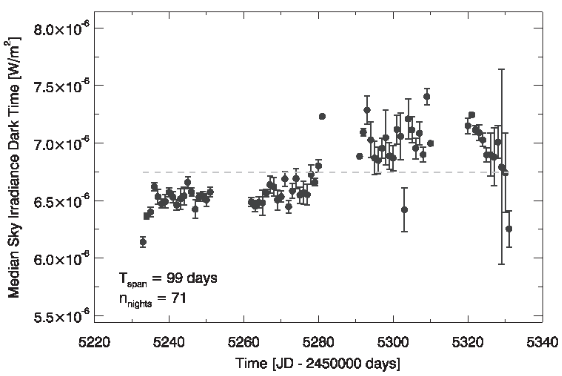


Fig. 3. Median night sky irradiance for Cerro Armazones.

file and get updated after each successful fit. The measured irradiance of the day and night is written into a file and plotted. Additional plots and files are generated like the median night sky irradiance and the proportion of clear time during the night for statistical purpose.

## 3. FIRST RESULTS

The continuous measurement of the night sky brightness gives us a detailed view on the conditions of the observing site. Short-term variations caused by, e.g. clouds, and long-term trends caused by, e.g. the seasonal appearance of the Milky Way, can be

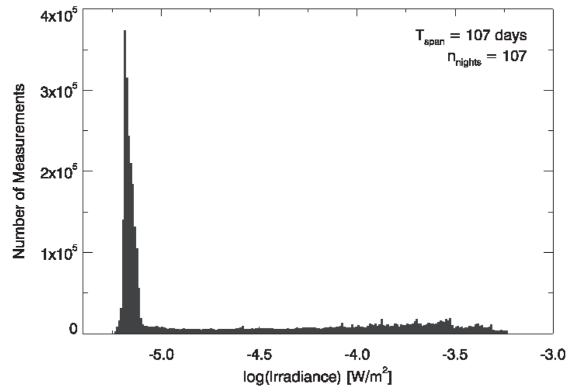


Fig. 4. Histogram of the measured irradiance during the night.

identified. Figure 3 shows the average night sky irradiance of Cerro Armazones derived from our data set. Only dark time was considered for this computation, i.e., only parts where the altitude of the Sun was $\leq -18°$ and where the altitude of the Moon was $\leq -5°$ were considered. In addition, the first two hours after the end and the last two hours before the beginning of the astronomical twilight were rejected from the computation to avoid contamination by the Zodiacal light. Only nights that fulfill all constraints are plotted. The error bars are the standard deviation of the measured irradiance during the night and are an indicator for the stability of the night sky irradiance, i.e., as smaller the error bar as stable the night sky irradiance. The change of the irradiance over time is caused by the seasonal appearance and disappearance of the Milky Way.

Figure 4 shows a histogram of the measured irradiance during the night of our data set obtained at Cerro Armazones. Only data are considered where the altitude of the Sun was $\leq -18°$. There are three distinct features visible: (1) The highest peak on the left side represents dark and clear nights. As narrower the peak as better the overall sky quality of the observing site, i.e. it is an indicator for the presence of clouds and artificial light sources. (2) Next to the first peak a smaller peak is present at a higher irradiance ($\log I = -5.1$ W m$^{-2}$). This is the contribution of the Milky Way, Zodiacal light, and sky glow. (3) The broad peak at the very right, around $\log I = -3.5$ W m$^{-2}$, is the contribution by the Moon. These features are not visible in light polluted areas. In such a case, the histogram would only show a single broad peak and clear nights would no longer distinguishable from nights where full moon is present.

## 4. CONCLUSION

The Lightmeter is a new sensitive device, which allows continuous measurements of the night sky brightness independent from the observing site and weather conditions. It covers the whole brightness range from day time down to the darkest night time conditions. The usage of the Sun and the Moon as natural calibrators keeps the hardware requirements low. We presented a first data set taken at Cerro Armazones and proofed the high sensitivity of the Lightmeter.

The high data sampling rate of 1 Hz allows real-time measurements of the night sky brightness which can be used to support astronomical observations, e.g. for cloud detection, and can contribute to site selection processes of future telescope facilities.

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