

## Night sky background at ASTRI Mini-Array site: correlation between the Sky Quality Meter fluxes and ASTRI-1 variance data

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The ASTRI Mini-Array, an array of nine innovative Imaging Atmospheric Cherenkov Telescopes with large field of view ( $10.6^\circ$ ), is an INAF project devoted to the study of gamma-ray sources emitting at very high energy in the TeV spectral band. It is situated at the Teide Astronomical Observatory, Instituto de Astrofísica de Canarias, on Mount Teide in Tenerife (Canary Islands, Spain), where the first telescope of the array, ASTRI-1, is operational since 2024 and a second telescope, ASTRI-3, is under construction. ASTRI Mini-Array cameras implement the so-called Variance method, an ancillary output dedicated to the imaging of the night sky background in the field of view. This method is based on the statistical analysis of the signal detected by the front-end electronics, whose variance is proportional to the flux impinging on the camera pixels. ASTRI-1 is also equipped with a Sky Quality Meter, an auxiliary device mounted on the back of the secondary mirror to measure the brightness of the night sky in the region pointed by the telescope. The field of view of the Sky Quality Meter is coaxial with the telescope and about two times larger ( $20^\circ$ ), providing integral information in units of mag/arcsec. A correlation of fluxes between Sky Quality Meter and Variance data has already been obtained with ASTRI-Horn, the ASTRI Mini-Array telescope prototype operating at the INAF "M.C. Fracastoro" observing station (Serra La Nave, Mount Etna, Italy). In this work we present the correlation between the Sky Quality Meter values of the sky brightness and the variance data from ASTRI-1. This correlation can be used to convert the Variance into absolute sky flux helping in identifying periods of high background levels. Knowing this correlation is useful for evaluating the instrumental duty cycle, preparing observation schedules, and discriminating among runs with different night sky background levels for the data acquisition and analysis processes.

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## 1. Introduction

The ASTRI Mini-Array is an innovative system of imaging atmospheric Cherenkov telescopes (IACTs) developed by the Italian National Institute for Astrophysics (INAF). It has been designed to operate in the very high-energy (VHE) gamma-ray domain, particularly above 10 TeV up to and beyond 100 TeV. The array consists of nine dual-mirror Schwarzschild–Couders telescopes optimized for wide-field observations ( $\sim 10^\circ$  field of view, FoV) and it is currently being deployed at the Teide Astronomical Observatory, Instituto de Astrofísica de Canarias, on Mount Teide in Tenerife (Canary Islands, Spain). The first telescope of the array, ASTRI-1, has been operational since mid-2024, while the second unit, ASTRI-3, is almost completed as evident from Figure 1.



**Figure 1:** ASTRI-1 (in the background) and ASTRI-3 (in the foreground): the first two telescope of the ASTRI Mini-Array installed on Mount Teide in Tenerife (Canary Islands, Spain).

Once completed, the array will contribute to give robust answers to a few selected open questions in the VHE domain such as the origin of cosmic rays, the study of extragalactic background light, gamma-ray bursts and multi-messenger transients, and the exploration of fundamental physics phenomena at extreme energies [1]. In addition to its scientific role, the Mini-Array serves as a precursor of CTAO-SST telescopes [2], allowing the validation of calibration strategies, control systems, and data analysis pipelines under real observational conditions.

ASTRI telescopes are based on an innovative design that combines Schwarzschild-Couder dual-mirror optics with a focal plane equipped with Silicon Photo-Multiplier (SiPM) sensor arrays. The camera electronics [3], operating in a custom peak-detector mode, also implement the *Variance method*. This performs the statistical analysis of the signals recorded by the front-end electronics in the absence of triggers, measuring the background light emitted as night sky brightness (NSB) [4]. In addition, the ASTRI Mini-Array is equipped with a Sky Quality Meter (SQM), which offers a quick evaluation of the sky conditions during observations by measuring the NSB in the optical band. Although the SQM and ASTRI cameras differ in both spectral response and FoV, the SQM measurements can be used to estimate the diffuse background level in the ASTRI camera pixels,

provided that a calibration or conversion factor between the SQM flux and the signal variance is determined.

In this work, we present an analysis aimed at establishing the correlation between the sky brightness measured by the SQM and the variance data recorded by ASTRI-1 during the observational campaign on the Crab Nebula conducted as part of the telescope's commissioning phase.

## 2. ASTRI-1

ASTRI-1 is the first telescope of the ASTRI Mini-Array to be installed on Mount Teide in Tenerife. Following the calibration of its optics and sensors, it successfully completed its commissioning phase, which included an extensive observing campaign on the Crab Nebula. Data obtained during this period were used to extract the source spectrum up to approximately 10 TeV [5]. The telescope was calibrated to meet its design specifications: the on-axis optical point spread function (PSF) encloses 80% of the light within a single pixel ( $0.19^\circ$ ); the gain variation across the focal plane is limited to  $\sim 4\%$ ; and the average optical cross-talk is around 4% [6].

The design of the telescope, based on that of the ASTRI-Horn prototype [7], foresees a camera composed by 37 photon detection modules (PDM) of SiPM detectors and managed by a specifically designed fast readout electronics. The electronics [3] operate using a custom peak-detection mode designed to capture the maximum amplitude of the SiPM pulses [8]. The readout chain is AC-coupled, so when the pixels are illuminated by a Poissonian source, the mean signal remains zero, while the signal variance scales proportionally with the photon rate. In addition, the camera implements the variance method, which performs a statistical analysis of the signals recorded by the front-end electronics during time intervals without camera triggers [4]. Since photons follow a Poisson time distribution, their fluctuations appear as signal dispersion in the absence of event triggers and are recorded by the variance method, enabling an indirect measurement of the NSB flux and of the stellar intensities in the FoV (see Fig 2). Consequently, the method allows for continuous monitoring of sky conditions, including the detection of clouds, stars or other transient features within the telescope's FoV. In particular, the relation that links the NSB flux to variance data [9] is:

$$\sigma^2 = \sigma_{dark}^2 + K\phi_{NSB} \quad (1)$$

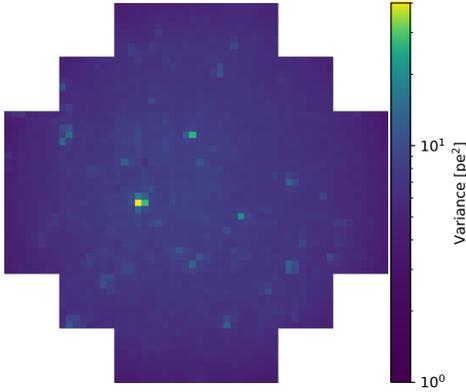
where  $\sigma^2$  is the measured variance,  $\sigma_{dark}^2$  represents the contribution from the sensor's dark noise, which is negligible compared to the NSB contribution [10],  $\phi_{NSB}$  is the NSB flux, and  $K$  is a proportionality constant that accounts for the overall efficiency of the telescope and the response of the readout electronics.

## 3. Sky Quality Meter

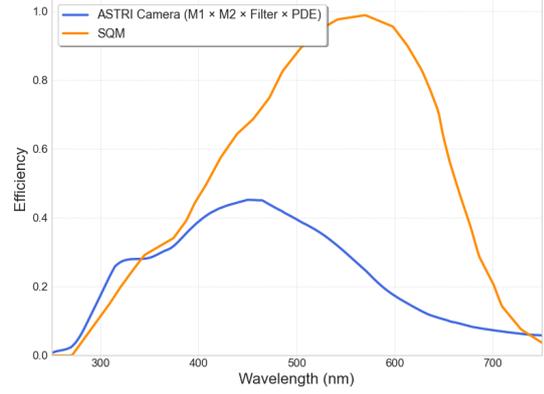
The SQM is installed on ASTRI-1 in a coaxial configuration, aligned with the telescope's optical axis to monitor at the same direction of the observed sky. The device is a factory-calibrated SQM-LE model<sup>1</sup>, which measures the integrated sky brightness within its FoV in units of mag/arcsec<sup>2</sup>, with an absolute accuracy of 10%. Its angular response has a full width at half maximum (FWHM)

<sup>1</sup><http://unihedron.com/projects/sqm-le/>

of  $20^\circ$ , allowing it to capture a broad region of the sky around the pointing direction. The SQM has a spectral response that peaks near 550 nm, within the visible range. This slightly differs from the optical throughput of ASTRI-1, which peaks in the blue wavelength range around 450 nm as shown in Fig. 3. Despite the SQM and ASTRI-1 are different both in spectral sensitivity and FoV, a correlation between the SQM-measured sky brightness and the variance data from ASTRI-1 is still achievable, with some caveats. Specifically, no clouds, planets, or bright stars should be present near the edge of ASTRI-1's FoV, as they can occasionally illuminate the camera plane and modify the correlation.



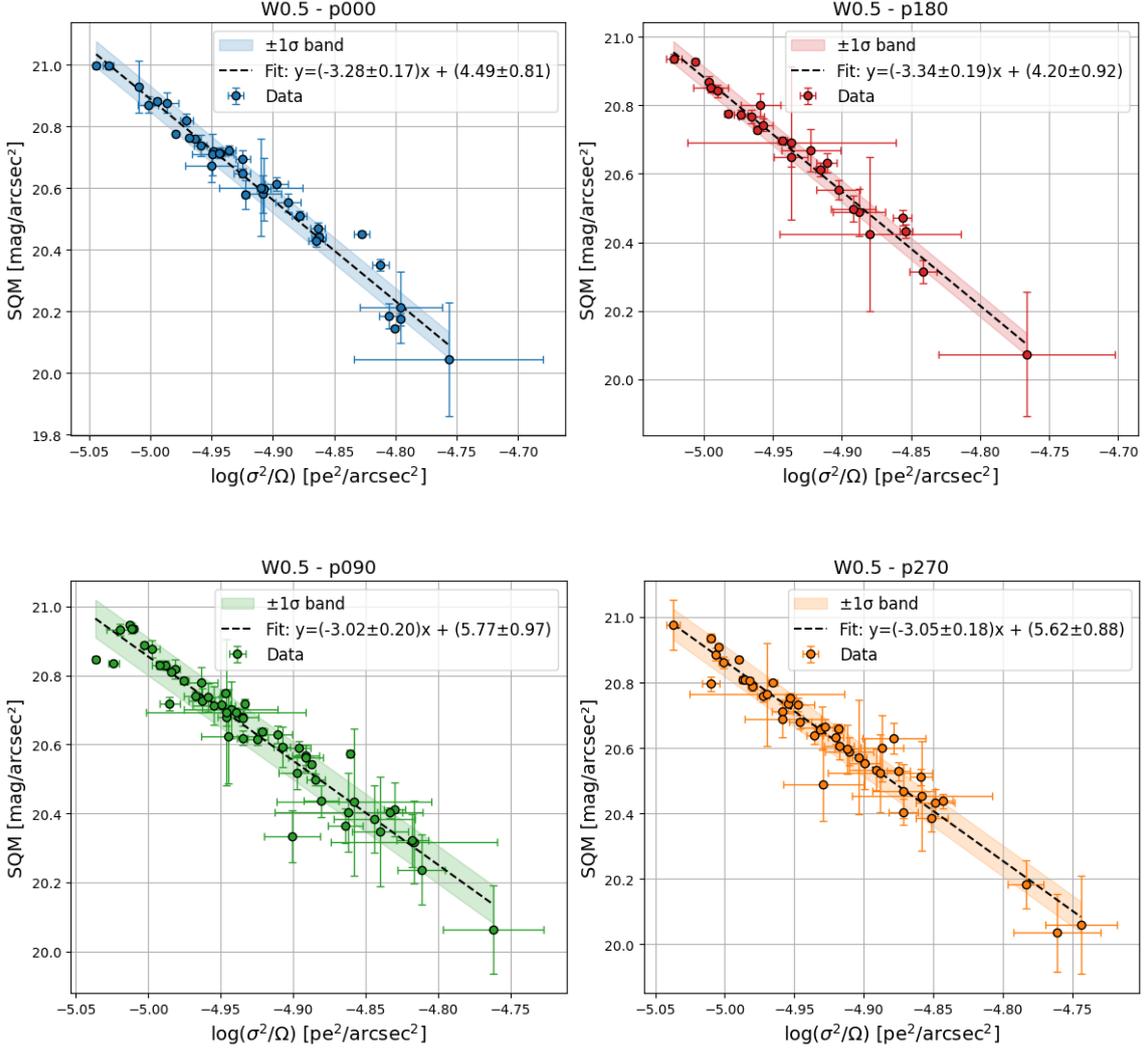
**Figure 2:** Image of variance in  $\text{pe}^2$  where stars up to magnitude 7 in the field of view are clearly visible. The brightest spot corresponds to  $\zeta$  Tauri.



**Figure 3:** SQM efficiency as function of the wavelengths (orange curve). For comparison, the blue line shows the ASTRI-1 camera detection efficiency obtained from the convolution of the reflectivity of the primary and secondary mirror, the camera's filter transmission and the SiPM's photon detection efficiency.

#### 4. Data analysis and results

The data analyzed in this study were collected from 2024 November 22 to 2025 January 24, during the ASTRI-1 observation campaign of the Crab Nebula. Throughout the campaign, the Crab was observed with different trigger levels depending on the moon phases and with various offsets to simultaneously measure the background and evaluate the telescope's off-axis performance [5]. In this work, we considered only the observations taken with an offset of  $0.5^\circ$  from the Crab direction and in a zenith angle range between  $5^\circ$  and  $60^\circ$ . These observations correspond to four distinct pointing directions, the coordinates of which are listed in Table 1. The data acquired during each night are structured into runs, each with a duration of approximately 30 minutes. For each run, the average variance was calculated, excluding pixels contaminated by starlight. In parallel, the average sky brightness was determined from simultaneous SQM measurements and expressed in units of  $\text{mag}/\text{arcsec}^2$ . The standard deviation within each run was adopted as the statistical uncertainty on the corresponding average. Figure 4 presents the SQM sky brightness (in  $\text{mag}/\text{arcsec}^2$ ) as a function of the logarithm of the variance (in  $\text{pe}^2/\text{arcsec}^2$ ) for each of the four pointing directions considered, with the corresponding  $1\sigma$  uncertainty.



**Figure 4:** Correlation between the SQM sky brightness and the  $\log(\sigma^2/\Omega)$  in different wobble pointing modes: W0.5p000, W0.5p090, W0.5p180, W0.5p270.

As a first step, we fitted the data points corresponding to each selected pointing direction using the following function:

$$\phi_{\text{SQM}} = A \log \frac{\sigma^2}{\Omega} + B \quad (2)$$

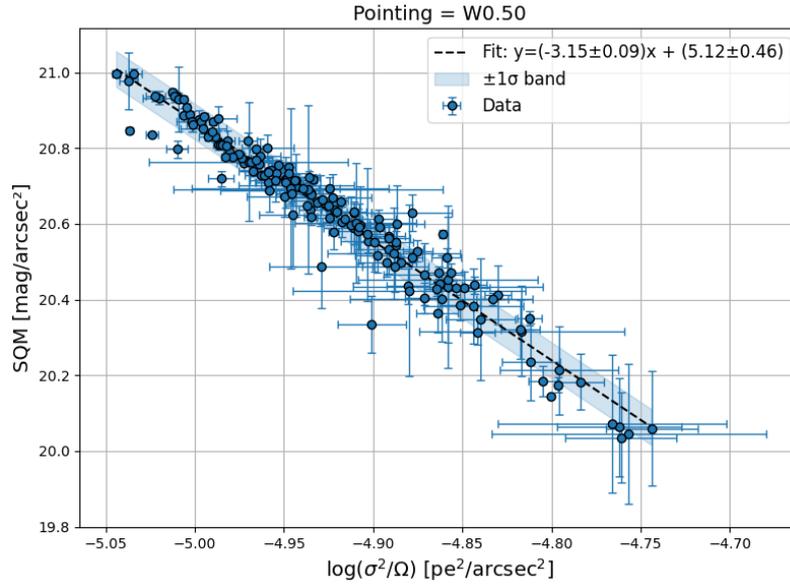
where  $\phi_{\text{SQM}}$  is the flux measured by the SQM,  $\sigma^2$  the variance,  $A$  and  $B$  the fitting parameters and  $\Omega$  the solid angle in arcsec subtended by the ASTRI camera pixel ( $684'' \times 684''$ ).

Table 1 reports the best-fit values of the model parameters, their associated 90% confidence intervals, and the corresponding reduced  $\chi^2$  values for each pointing direction. The results clearly indicate that the data are well described by Eq. 2, with reduced  $\chi^2$  have all acceptable values being within  $1\sigma$  of the relative distribution. Moreover, the best-fit parameters obtained for the

Table 1

Pointing Code	Coordinate		# Obs.	$A$	$B$	$\tilde{\chi}^2$
	Ra (deg)	Dec (deg)				
W0.5p000	84.168	22.015	36	$-3.28 \pm 0.17$	$4.49 \pm 0.81$	1.06
W0.5p090	83.629	22.515	54	$-3.02 \pm 0.20$	$5.77 \pm 0.97$	1.04
W0.5p180	83.089	22.015	25	$-3.34 \pm 0.19$	$4.20 \pm 0.92$	1.09
W0.5p270	83.629	21.515	47	$-3.05 \pm 0.18$	$5.62 \pm 0.88$	1.04

four independent pointing directions are consistent within uncertainties, suggesting no significant differences on the NSB level in the considered pointing configuration. This consistency justifies a single fit of the combined data set using the same function. The best-fit parameters obtained from the joint fit are  $A = -3.15 \pm 0.09$  and  $B = 5.16 \pm 0.46$ , with a corresponding reduced  $\tilde{\chi}^2$  of 1.013. Figure 5 presents the SQM sky brightness (in mag/arcsec<sup>2</sup>) as a function of the logarithm of the variance (in pe<sup>2</sup>/arcsec<sup>2</sup>) for all the four pointing directions considered.



**Figure 5:** Correlation between the SQM sky brightness and the  $\log(\sigma^2/\Omega)$  in different all the wobble W0.5 pointing modes.

## 5. Conclusion

We presented a detailed analysis of data collected by the ASTRI-1 telescope and the SQM during selected runs from the ASTRI-1 commissioning observation campaign. The primary goal of this study was to investigate the correlation between the sky brightness, as measured in mag/arcsec<sup>2</sup> by the SQM, and the variance recorded by the ASTRI-1 camera in pe<sup>2</sup>. This correlation is particularly relevant for understanding and quantifying the impact of the NSB on the performance of IACTs and for producing correct Monte Carlo simulations of the observed data.

The results demonstrate that a clear and consistent relationship exists between the two measurements. Specifically, this correlation enables the estimation of the NSB level in the ASTRI camera based on the SQM sky brightness, and conversely, allows for the conversion of variance data into absolute sky flux values. This approach provides a practical method for assessing the observational conditions and calibrating background contributions for the ASTRI Mini-Array simulation systems. [11, 12]. Nevertheless, it is crucial to highlight that the validity of this correlation is contingent upon the absence of clouds, bright stars, or planets at or near the edge of telescope’s FoV. Such sources can introduce fluctuations in the variance measurements altering the correlation.

It is also important to note that, while the numerical values of the best-fit parameters derived from the correlation function are specific to the pointing direction and instrumental configuration used during the campaign, the underlying methodology is broadly applicable. In this context, the analysis conducted here serves not only as a validation of the ASTRI-1 system’s performance but also as a valuable test-bench for the future implementation of this technique in the Cherenkov Telescope Array Observatory’s Small-Size Telescopes (CTAO-SSTs). As ASTRI-1 shares key technological features with the CTAO-SST design, including the dual-mirror Schwarzschild-Couder optical layout and SiPM-based focal plane, the results presented in this work support the use of similar background estimation methods in the data-taking campaigns of the next-generation observatories. This reinforces the role of ASTRI-1 as a technological and methodological precursor to the CTAO project, helping to refine tools and procedures that will be crucial in future high-energy astrophysical observations.

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