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# Ultra-violet imaging of the night-time earth by EUSO-Balloon towards space-based ultra-high energy cosmic ray observations.

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## 166 Abstract

The JEM-EUSO (Joint Experiment Missions for the Extreme Universe Space Observatory) program aims at developing Ultra-Violet (UV) fluorescence telescopes for efficient detections of Extensive Air Showers (EASs) induced by Ultra-High Energy Cosmic Rays (UHECRs) from satellite orbit. In order to demonstrate key technologies for JEM-EUSO, we constructed the EUSO-Balloon instrument that consists of a  $\sim 1 \text{ m}^2$  refractive telescope with two Fresnel lenses and an array of multi-anode photo-multiplier tubes at the focus. Distinguishing it from the former balloon-borne experiments, EUSO-Balloon has the capabilities of single photon counting with a gate time of 2.3 µs and of imaging with a total of 2304 pixels. As a pathfinder mission, the instrument was launched for an 8 hour stratospheric flight on a moonless night in August 2014 over Timmins, Canada. In this work, we analyze the count rates over  $\sim 2.5$  hour intervals. The measurements are of diffuse light, e.g. of airglow emission, back-scattered from the Earth's atmosphere as well as artificial light

sources. Count rates from such diffuse light are a background for EAS detections in future missions and relevant factor for the analysis of EAS events. We also obtain the geographical distribution of the count rates over a  $\sim$ 780 km<sup>2</sup> area along the balloon trajectory. In developed areas, light sources such as the airport, mines, and factories are clearly identified. This demonstrates the correct location of signals that will be required for the EAS analysis in future missions. Although a precise determination of count rates is relevant for the existing instruments, the absolute intensity of diffuse light is deduced for the limited conditions by assuming spectra models and considering simulations of the instrument response. Based on the study of diffuse light by EUSO-Balloon, we also discuss the implications for coming pathfinders and future space-based UHECR observation missions.

<sup>167</sup> Keywords: EUSO-Balloon, JEM-EUSO, ultra-high energy cosmic ray,

- <sup>168</sup> extensive air shower, airglow
- <sup>169</sup> *PACS:* 95.55.Vj 95.85.Ry, 96.50.sd, 92.60.hw,

# 170 **1. Introduction**

Ultra-High Energy Cosmic Rays (UHECRs) with energies,  $E_0$ , of several 171 times greater than  $10^{19}$  eV are extremely rare events and their origin is not 172 yet known [1]. To resolve this long-standing problem, it is essential to observe 173 large numbers of UHECRs for the systematic study of their arrival direction 174 distribution on the celestial sphere. Recent reports by the Pierre Auger 175 Observatory (Auger) [2] and the Telescope Array (TA) [3] agree that, despite 176 a possible discrepancy in the energy scales, the observed energy spectra show 177 suppression of the fluxes of UHECRs above  $\sim 5 \times 10^{19}$  eV in comparison to an 178 extrapolation from lower energies [4]. Above this energy, UHECRs have been 179 observed with the fluxes of the order of a few events per square kilometer per 180 century or even millennium. 181

Since the early 21st Century, large-scale ground-based UHECR observations
have been led by Auger [5] and TA [6] using particle detector arrays that cover

an observation area,  $S_{\rm obs}$ , of  $\sim 3000 \text{ km}^2$  and  $\sim 700 \text{ km}^2$ , respectively. Cosmic 184 rays are observed by detecting secondary particles in the induced Extensive Air 185 Showers (EASs) [1]. These experiments have their exposures to UHECRs in 186 different parts of the celestial sphere according to their geographic positions. 187 Recently excesses of UHECRs are reported as the middle-scale anisotropy in 188 the arrival direction distribution above  $\sim 8 \times 10^{18}$  eV by Auger [7] and above 189  ${\sim}5\times10^{19}$  eV by TA [8, 9], respectively. At the even higher energies, still larger 190 exposures are required to study it in more detail. 191

Both experiments also operate a few stations of multiple 'fluorescence 192 telescopes' each of which has a  $\sim 10 \text{ m}^2$  reflector and an array of Photo-Multiplier 193 Tubes (PMTs) at the focus [10, 11]. Cosmic rays are observed by the 194 'fluorescence technique', imaging the Ultra-Violet (UV) fluorescence light 195 emitted from the nitrogen molecules excited by the charged particles in the 196 EAS [1]. This light has a characteristic line spectrum in the  $\sim 290-430$  nm 197 band [12]. EAS events are seen as a bright point-like spot moving at the speed 198 of light above the 'background' light. Such light originates from both natural, 199 i.e., terrestrial and astronomical, and artificial light sources and increases the 200 noise level on the instrument. 201

Since the 1980s, space-based UHECR observations by means of the 202 fluorescence technique have been conceptually investigated and several missions 203 have been proposed [13, 14, 15, 16]. A single telescope with a few tens of 204 degrees wide Field-of-View (FoV) from a satellite orbit allows utilizing the 205 night-time atmosphere as a vast particle calorimeter to efficiently increase the 206 exposure over the whole celestial sphere. The EAS signals are only detectable 207 when significantly above the noise level. The energy and arrival direction of 208 the incident UHECRs are determined by analyzing the spatial and temporal 209 development of such signals above this level [17, 18, 19]. In this way, it 210 is important to understand the noise level when estimating the detection 211 capabilities of the instruments and the quality of data analysis. 212

In 2016, the TUS instrument was launched to start space-based UHECR observations in an orbit at  $\sim$ 500 km above sea level (asl.) [20]. Using a  $\sim$ 2 m<sup>2</sup> <sup>215</sup> reflective Fresnel telescope with 256 PMTs, it covers a  $\sim 9^{\circ}$  FoV corresponding to <sup>216</sup> an order of  $S_{\rm obs} \sim 6000 \text{ km}^2$  area. Simulation studies show that this instrument <sup>217</sup> is capable of detecting EASs from UHECRs with  $10^{20}$  eV energies.

The JEM-EUSO (Joint Experiment Missions for the Extreme Universe 218 Space Observatory) program [21] is one of the mainstream projects. As the 219 baseline, an ultra-wide FoV telescope was proposed using  $\sim 4.5 \text{ m}^2$  refractive 220 optics with three double-sided Fresnel lenses, aiming at UHECR observations 221 over an  $S_{\rm obs} \sim 10^5 \ {\rm km^2}$  area from the International Space Station (ISS) at 222  $\sim 400$  km asl. [22]. This optical system was designed to achieve a wide enough 223 FoV with high enough Signal-to-Noise Ratio (SNR) on the photo-detector, 224 this being a requirement in the development of such detectors. To test the 225 key technologies for JEM-EUSO, we conducted and planned pathfinders on 226 the ground, on balloons and the ISS. Including the experience from TUS, the 227 outcomes from these pathfinders can be also applied to future missions such as 228 KLYPVE-EUSO [23, 24] and POEMMA [25]. 229

In August 2014, a stratospheric flight of EUSO-Balloon was carried out from Timmins (ON), Canada. It reached a float altitude at ~38 km asl. The EUSO-Balloon mission allowed for a full end-to-end test of a JEM-EUSO prototype consisting of the key subsystems for a space experiment. The instrument performed UV imaging of the night-time earth that allows for a better understanding and scientific interpretation of future space-based UHECR observations.

For efficient detections of EASs, given constraints on the data downlink 237 capacity of the mission, the noise level on the photo-detectors should be carefully 238 monitored. It affects not only the trigger algorithms for real-time EAS detection 239 in orbit, but also introduces errors in offline, ground-based data analysis. In this 240 work, we present the results and discussions on such noise from UV light seen 241 by EUSO-Balloon from both natural and artificial sources. Hereafter, we define 242 'background' light as the sum of any light in the  $\sim 300-500$  nm wavelength 243 band from the atmosphere or the earth below, as seen by the nadir-pointing 244 instrument. 245

This paper is organized as follows: Section 2 summarizes the existing 246 knowledge of UV light from the night-time earth and atmosphere and the 247 measurements obtained by the former balloon experiments. Section 3 describes 248 the specifications of the EUSO-Balloon mission and the data used in this 249 work. Section 4 presents the methods of the analysis. Section 5 shows the 250 main results. Section 6 gives interpretations of the results, implications for 251 space-based UHECR observations and the outlook for future missions. Section 7 252 concludes this work. 253

# 254 2. UV light from the night-time earth

#### 255 2.1. UV light as a background for UHECR observations

In terms of the effect on UHECR observations, the background consists of 256 light components from both persistent and local sources in the UV band; the 257 former is due to diffuse light sources illuminating the whole FoV, thus reducing 258 the observation time and the latter appears transiently, reducing a part of the 259 instantaneous observation area. The local component is often so intense that the 260 trigger algorithms for detecting EAS events are hampered. In terms of studying 261 the background light relevant for the detections of EASs, only diffuse light plays 262 a role and this component should be quantified for the impact on the noise due 263 to its intensity. 264

The distribution of the local light sources such as cities can be predicted in 265 advance along the orbit of a space-based observatory. Influence from the isolated 266 light sources only occurs where such sources pass through the FoV. The trigger 267 algorithms can be designed to remain operational in the rest of the FoV [26, 27]. 268 At higher geomagnetic latitudes, the entire FoV may occasionally be filled by 269 the aurora. This can be monitored by the telescope itself and recognized by 270 using external information about the geomagnetic storm [28]. Sudden events 271 such as lightning and transient luminous events persist for durations of the order 272 of milliseconds. This is far slower than the tens-to-hundreds-microsecond-scale 273 of EASs, thus the affected area and time can be recognized. On these occasions, 274

it is only important to quantify the affected fraction of the instantaneousobservation area rather than the light intensity.

On moonless, dark nights, the airglow is the dominant source in 277 the  $\sim 300-400$  nm band. It is emitted when the disassociated oxygen atoms 278 recombine to molecules at around 80-100 km asl. near the mesopause. The 279 emission mechanisms are well understood. They produce a mixture of the 280 Herzberg I, Herzberg II and Chamberlain emissions [29]. The intensity of the 281 airglow emission, as well as by the position over the Earth, changes on various 282 time scales, i.e., seasonally, daily or even more frequently [30, 31, 32]. In orbit, 283 the airglow light is measured as a sum of the direct light from the emission 284 altitude and back-scattered light from the atmosphere, clouds, and the Earth's 285 surface. 286

By pointing the instrument downwards, extraterrestrial light such as starlight and zodiacal light originating above the flight level only contributes to the noise as back-scattered light. Such situations are realized when the Moon is near the New Moon phase or lies near the horizon. The properties of such light have been discussed in Refs. [22, 33] and references therein.

#### 292 2.2. Former balloon-borne measurements

As part of the drive for space-based UHECR observations, there have been several balloon-borne experiments aiming at investigating background light [34, 35, 36, 37]. A major goal of these experiments was to determine the absolute intensity,  $I_0$ , of the diffuse light under clear atmosphere conditions in moonless night. Results have been presented by two groups.

The Background Bypass (BaBy) balloon experiment [34] was first carried out over the land and sea off Sicily, Italy, at ~26 km asl. on July 30, 1998. The instrument was purely designed for diffuse light measurements that consisted of two sets of collimators and PMTs mounted with UV band-pass filters. The estimated  $I_0$  value over the sea without ambient light of the populated areas was ~400-450 photons m<sup>-2</sup> sr<sup>-1</sup> ns<sup>-1</sup> in the 300-500 nm band. The other flight of BaBy reaching ~39 km asl. took place over the Mediterranean Sea on July 11, 2002 [35]. The average  $I_0$  value was 310 photons m<sup>-2</sup> sr<sup>-1</sup> ns<sup>-1</sup> in the 300-400 nm band. Another flight attempt in 2001 was reported with more than twice the intensity in comparison with the above value. We consider that it was due to the low flight altitude of ~15-30 km and possible light pollution by the artificial light.

The NIGHTGLOW balloon experiment took place over Texas, USA, at 310  $\sim 30$  km asl. on July 5, 2000 [36]. The instrument was composed of elements 311 used for real fluorescence telescopes; a  $\sim 36$  cm diameter spare mirror and UV 312 band-pass filters from the High Resolution Fly's Eye (HiRes) experiment [38] 313 and two PMTs from the Fly's Eye experiment [39]. These filters were selected 314 for the maximum SNR for EAS detections. The  $I_0$  value in the nadir direction 315 was found to be  $300\pm41$  photons m<sup>-2</sup> sr<sup>-1</sup> ns<sup>-1</sup> in the 300-400 nm band. 316 By pointing the instrument to the zenith, the total intensity of the downward 317 component was estimated to be  $691 \pm 34$  photons m<sup>-2</sup> sr<sup>-1</sup> ns<sup>-1</sup>. 318

The latest discussions on the  $I_0$  values were given in this Journal by NIGHTGLOW and by the Tatiana satellite [40]. Even under similar conditions, it is difficult to compare different measurements due to the variability of airglow emissions and responses of the instruments. These values have been used as references for simulations to estimate the expected noise level on the instrument when designing fluorescence telescopes.

# 325 3. EUSO-Balloon

EUSO-Balloon was a pathfinder mission for the JEM-EUSO program led by the French space agency CNES (*Centre National d'Études Spatiales*) in coordination with the JEM-EUSO collaboration. A full description of the mission and scientific payload is specified in Ref. [41].

# 330 3.1. The EUSO-Balloon telescope

The EUSO-Balloon telescope is the main instrument of the balloon payload with a total mass of 467 kg. It is installed with crash rings, designed to protect the instrument in the case of landing on dry land as well as a floater to keep the electronics subsystems dry in the case of a possible water landing [42, 43].

EUSO-Balloon is capable of imaging in the UV band. This is a 335 major difference when compared to the former experiments. The telescope 336 consists of two Fresnel lenses made of 8 mm thick PMMA, UV transmitting 337 polymethylmethacrylate [44, 45]. Based on the technologies developed for 338 JEM-EUSO [46], the lenses were fabricated as 1.2 m diameter circular lenses 339 and then were cut to form a square of side 1 m with round corners. The nominal 340 entrance aperture,  $S_{opt}$ , is 0.96 m<sup>2</sup>. To avoid any damage during landing, the 341 optics is recessed inside the overhanging walls. These walls are extended beyond 342 the front lens to act as a baffle, blocking photons from large off-axis angles. 343

A Photo-Detector Module (PDM) [47] is placed at the focus of the optics. It is formed of 36 (=  $6 \times 6$ ) Multi-Anode PMTs (MAPMTs; Hamamatsu R11890-M64) [48, 49]. They are aligned with a 27.5 mm pitch. Nine squares of four (=  $2 \times 2$ ) MAPMTs are both mechanically and operationally grouped to the units called Elementary Cells (ECs). Excluding the central unit, the ECs are slightly inclined up to 2.48° to approximately follow the aspherical geometric focal surface of the optics.

Every MAPMT has 64 channels in an array of  $8 \times 8$  pixels. With each pixel being a square of 2.88 mm on a side, the photocathode of an MAPMT effectively covers a square area of side ~23 mm (=  $8 \times 2.88$  mm). A 2 mm thick band-pass filter, Schott BG3 [50], is mounted on each MAPMT. The filters have a surface dimension of a 27 mm square, allowing the collection of some photons falling on the dead spaces between MAPMTs.

The sensitivity of the instrument is determined by the detection efficiency of the MAPMTs, the transmittance of the BG3 filters and the response of the optical system. The overall efficiency is highest in the  $\sim 330-400$  nm band where dominant lines of fluorescence light lie to give a more precise energy estimation of the incident UHECRs. The sensitive range extends between  $\sim 250$ and  $\sim 500$  nm. The lower limit is due to the transmittance of PMMA lenses, while the upper limit is given by that of BG3 filters and the quantum efficiency of the MAPMTs. It is worth mentioning that the sensitivity above ~400 nm allows the collection of more of the Cherenkov light produced in the EASs. This light is in general not desirable for ground-based fluorescence telescopes since it introduces uncertainties in the analysis of detected EAS events [51]. Seen from above, such light is back-scattered from the Earth's surface or clouds and allows for a more precise determination of the arrival direction of UHECRs by constraining the geometry of EAS events [17, 52].

For the control of electronics subsystems, the Data Processor (DP) 371 system [53] is employed. It controls front-end electronics, provides signals 372 for time synchronization and triggers, handles the interfaces to tele-commands 373 and to the telemetry system, and operates many other tasks. On a total of 374  $2304 (= 36 \times 64)$  channels, single photon counting was performed. Data used in 375 this work were acquired by two different trigger modes using the CPU command 376 at  $\sim 19$  Hz or the GPS synchronous signals at 20 Hz. Following a trigger, 377 128 samples, or one 'packet', of counts, n, were acquired on all pixels every 378 2.5  $\mu$ s. The readout duration,  $\tau_{GTU} = 2.3 \ \mu$ s, of each sample is called the Gate 379 Time Unit (GTU), hereafter [54, 55]. 380

This duration was originally chosen to be  $2.5 \ \mu s$ . This is the time that it 381 takes light to travel through the atmosphere across one pixel as imaged by the 382 original JEM-EUSO design from the ISS [56]. The choice of 128 samples was 383 made for buffering the data of EAS events seen in a PDM of JEM-EUSO as 384 well as a sufficient time before and after the event. These parameters have been 385 unchanged in the updated designs. The EUSO-Balloon instrument represents 386 one detection module of the proposed future space instruments which may have 387 more than 50 PDMs [24]. Thus it uses a similar time scale and sampling in the 388 data acquisition despite the much faster apparent speed of light crossing the 389 FoV. 390

In this work, we define a reference Cartesian coordinate system for the analysis of the acquired data. Seen from the optical axis through the lenses, we take the reference x- and y- axes, to be parallel to the sides of the PDM and the lenses, projected on the photocathode plane of the central EC unit.

#### 395 3.2. The EUSO-Balloon flight

The flight of EUSO-Balloon was carried out on the night of August 24/25, 2014. Unless otherwise noted, the time is given hereafter in UTC on August 25, 2014.

EUSO-Balloon was launched from the Timmins Stratospheric Balloon Base 399 at the Timmins Victor M. Power Airport; Latitude (Lat.) 48°34'13" N, 400 Longitude (Long.)  $81^{\circ}22'05''$  W and 296 m asl., at 00:54 (on August 24 at 401 20:54 EDT; UTC -4). Between 03:08 and 08:08, the EUSO-Balloon telescope 402 was operated pointing towards the nadir. The position and attitude during 403 the flight were monitored by the on-board GPS receivers. The attitude of the 404 EUSO-Balloon telescope was adjusted and checked before launch. Thus, the 405 GPS data allow the estimation of the ground position of the optical axis. 406

At 08:20, the EUSO-Balloon telescope was separated from the balloon and descended towards one of the 'driest' landing zones along the flight track. At 08:59, it splashed down in a small solitary lake (Lat. 48°39'10" N, Long. 82°41'14" W; 303 m asl.). Thanks to the protective design that shields all sensitive components in the event of a water landing [43], EUSO-Balloon was recovered undamaged and still fully operational.

In this work, we only use the data acquired in the Time interval of Interest (ToI) between 03:08 and 05:48. It was during a dark, moonless night, excluding periods of astronomical twilight. The instrument was operating in its nominal mode, allowing for uncertainties in the subsequent analysis to be minimized. After this time interval, various engineering tests were conducted with a variety of setups and operation modes, for which the analysis would have been more complex and uncertain.

Figure 1 displays the GPS ground track of the EUSO-Balloon optical axis by the solid curve. The bold curve denotes the track during the ToI. The launch and landing positions are marked in addition to the hourly positions. The dashed lines enclose the Region of Interest (RoI) for this work. The color scale represents the Visible band Digital Number (VDN) from the 2013 DMSP (Defense Meteorological Satellite Program) satellite data [57]. VDN scales to the fluxes in the  $0.35-2 \ \mu m$  band by 64 integer levels. We make use of the annual average data in cloud-free conditions given every 30" grid in geographic coordinates, i.e., at a resolution of ~610 m on the east-west and ~930 m on the north-south directions. The VDN is 0 in most of the RoI, while the rest is registered with a VDN of 4 or higher.

<sup>431</sup> During the ToI, EUSO-Balloon traveled ~80 km to the west. The average <sup>432</sup> elevation,  $h_0$ , of the terrain along the track was 296 m asl. The ground track <sup>433</sup> of the EUSO-Balloon telescope includes populated and industrial zones around <sup>434</sup> Timmins, while most of the other areas were forests and small lakes. There are <sup>435</sup> potentially intense artificial light sources around Kamiskotia Lake, the largest <sup>436</sup> water body in the RoI, with a diameter of 2.5 km. The ground track also passed <sup>437</sup> ~3.4 km from Montcalm Mine in the western part of the RoI.

Figure 2 displays the altitude,  $H_0$ , of the EUSO-Balloon telescope as a function of the UTC time, t. EDT local time is shown on the top. The ToI and the dark night period are indicated by the arrows.

At the beginning of the ToI, the EUSO-Balloon telescope reached 36.4 km asl. Until 03:30, it continued ascending to the float altitude of about 38.2 km which was maintained within a  $\sim \pm 0.2$  km oscillation with a  $\sim 5$  min period. At this altitude, the atmospheric pressure is  $\sim 4$  hPa. To avoid coronal discharge at such a low pressure that could lead to a breakdown of the entire mission, we limited the high voltage applied on the MAPMTs to -950 V against the nominal operational voltage of -1100 V.

The EUSO-Balloon telescope was freely rotating around the optical axis. To describe such a rotation, we define the orientation,  $\Phi_0$ , of the telescope by the eastward angle, measured from the true north to the *x*-axis of the PDM. Hereafter, azimuth with respect to the horizontal coordinates is defined in the same way.

Figure 3 displays the orientation  $\Phi_0$  of the EUSO-Balloon telescope as a function of the time t. North, east, south and west directions correspond to  $0^{\circ}, +90^{\circ}, \pm 180^{\circ}$  and  $-90^{\circ}$ , respectively. The ToI is indicated by the arrow.

456 During the ToI, the EUSO-Balloon telescope tended to rotate eastward and

<sup>457</sup> made four rotations in total. It also exhibited a torsion pendulum motion with <sup>458</sup> a typical period of ~153 s, estimated by Fourier transform. In the earlier part <sup>459</sup> of the ToI, the maximum amplitude of the torsion pendulum motion was  $\pm 150^{\circ}$ . <sup>460</sup> The angular velocity,  $\dot{\Phi}_0$ , was 7° s<sup>-1</sup> at maximum. After having reached the <sup>461</sup> float altitude, the torsion driven motions damped over time.

The pointing direction of the optical axis of the telescope also varied with a similar trend. The maximum off-axis angle from the nadir is estimated to be  $\sim 1.8^{\circ}$  [58]. Such variation of the attitude is taken into account in the ground track shown on Fig. 1 which is used as a reference for location during the analysis.

From the GPS data, the ground speed,  $v_0$ , of the EUSO-Balloon telescope ranged between 2 and 15 m s<sup>-1</sup> with an average  $\langle v_0 \rangle$  of 8 m s<sup>-1</sup> ( $\approx 31$  km h<sup>-1</sup>) during the ToI. The typical ground speed at the float altitude was  $\sim 8-12$  m s<sup>-1</sup> between 03:30 and 04:45. It then tended to slow down.

<sup>471</sup> Chasing the ground track of the EUSO-Balloon telescope, we operated a <sup>472</sup> helicopter at a flight altitude of  $\sim 3$  km from where we generated EAS-like events <sup>473</sup> by using a UV laser [59]. LED and xenon flashers were also used to provide <sup>474</sup> calibration sources. Between 03:21 and 05:48,  $\sim 1.5 \times 10^5$  laser shots followed <sup>475</sup> by the flasher events were generated in various horizontal directions from the <sup>476</sup> helicopter. A small fraction of such events are included in the data used in this <sup>477</sup> work.

# 478 3.3. The elementary data

During the ToI, the EUSO-Balloon telescope was operated to acquire a packet from every pixel by the DP signals at ~19 Hz except for the time interval between 04:36 and 05:13 when the acquisition rate was at 20 Hz. In the intervals of 03:47-03:51 and 05:13-05:16, the telescope was operated in a different mode for the system checks [60]. Excluding these checks, ~150 min (= 2.5 hours) of the operation time was assigned for the purpose of this work.

The total number, M, of packets used in the analysis is  $\sim 1.5 \times 10^5$ . Let  $n_{i,j}$ be the count readout on the *i*-th pixel at the *j*-th sample in the packet. The

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487 average count rate  $\langle n \rangle$  over a packet is given as follows:

$$\langle n_i \rangle = \frac{1}{128} \cdot \sum_{j=1}^{128} n_{i,j},$$
 (1)

where the pixel number is hereafter referenced by the subscript *i*. The  $\langle n \rangle$  value represents the average for the interval of 320 µs (= 128 × 2.5 µs) with the total gate time of 294 µs (= 128 × 2.3 µs). The time resolution is ~52 ms (≈1/19 [Hz]) given by trigger rates. This value in most cases represents the average noise level due to diffuse light.

Figure 4 displays examples of the  $\langle n \rangle$  values of all the pixels on the PDM. Malfunctioning pixels are blackened out. Along with the GPS data, the left and right panels correspond to the packets acquired at (i) 03:09 and (ii) 05:47, respectively. The dimension of the PDM is shown in the right.

For further analysis, we use such 'snapshots' of the  $\langle n \rangle$  values from Eq. (1) 497 obtained every packet, along with the GPS data to form the elementary data 498 set. These examples are chosen from the data obtained at the beginning and 499 the end of the ToI. At the time of Example (i), EUSO-Balloon was flying 500 above the eastern part of Timmins. Pixels with  $\langle n \rangle$  values exceeding those 501 of the adjacent pixels, hereafter referred to as 'hotspots', can be seen. As for 502 Example (ii), EUSO-Balloon was above the forest at the west end of the RoI 503 where no significant artificial light sources are expected. 504

# 505 4. Analysis

The main goal of the analysis is to obtain the temporal variation of the UV light measured by the EUSO-Balloon telescope and its image projected on geographic coordinates. In this section, we describe the analysis procedures using the elementary data, results of the post-flight calibration [54, 55, 58, 61] and relevant simulations.

511 4.1. Count rate determination

In this work, we use the average count rate  $\langle n \rangle$  over a packet from Eq. (1). The readout count *n* shows non-linearity with respect to the number,  $n_{\rm pe}$ , of <sup>514</sup> photoelectrons (pe) collected on the first dynode. This relation is expressed by
<sup>515</sup> the following theoretical formula [62]:

$$n \simeq n_{\rm pe} \cdot \exp\left(-\frac{\tau_0}{\tau_{\rm GTU}} \cdot n_{\rm pe}\right),$$
 (2)

where  $\tau_0 \sim 30$  ns corresponds to the double pulse resolution in photon counting 516 by the readout electronics and was experimentally determined [63]. Substituting 517 the  $\langle n \rangle$  value given by Eq. (1) for the *n* value in this equation, we can solve for 518 the  $n_{\rm pe}$  value. The solution is double-valued in most cases. We choose the lower 519 value of the solutions and call the 'count rate', N, in units of pe pixel<sup>-1</sup>  $GTU^{-1}$ . 520 For n=1 and 10 counts pixel<sup>-1</sup> GTU<sup>-1</sup>, the corresponding N values 521 are 1.01 and 11.7 pe pixel<sup>-1</sup> GTU<sup>-1</sup>, respectively. In the case of  $n \gtrsim$ 522 28 counts pixel<sup>-1</sup> GTU<sup>-1</sup>, no solution exists. Thus we force  $\langle n \rangle$  values to have 523 an upper limit of ~28. This gives the bound of N < 68 pc pixel<sup>-1</sup> GTU<sup>-1</sup>. The 524 fraction of such cases is  $\sim 10^{-5}$  of the whole  $\langle n \rangle$  data set. 525

As seen in Example (ii) of Fig. 4, there are relative differences among pixels 526 mainly due to the different efficiencies. To correct such differences, we apply 527 the result from the post-flight calibration of the PDM [54]. For all the pixels, 528 'pixel efficiencies',  $\varepsilon$ , in terms of the ratio of the collected  $n_{\rm pe}$  to the number of 529 photons incident on the pixel area through the BG3 filter, were determined at 530 a wavelength,  $\lambda$ , of 378 nm. Using a calibrated NIST photodiode with 1.5% 531 accuracy, a few pixels in each MAPMT were absolutely calibrated with an 532 accuracy of better than 3% based on the technique developed in Ref. [64]. The 533 rest of the pixels were then relatively calibrated. 534

For the detection efficiency,  $\varepsilon_{det}$ , the product of the photocathode's quantum efficiency and the collection efficiency of the MAPMT, and transmittance,  $T_{BG3}$ , of the BG3 filters, the wavelength dependence of the  $\varepsilon$  efficiency is given as follows:

$$\varepsilon_i(\lambda) = \varepsilon_{\det,i}(\lambda) \cdot T_{\mathrm{BG3},i}(\lambda). \tag{3}$$

The  $T_{BG3}$  value also accounts for the geometrical effect whereby the filter acts as a light guide and thus tends to slightly increase pixel efficiencies at the outer part of each MAPMT.

To ensure a high quality data set, we eliminated the malfunctioning pixels 542 that are mostly due to the limited voltage [55, 63]. We further select the best 543 calibrated 650 pixels to limit the absolute uncertainty  $\Delta \varepsilon < 5\%$ , leading to 544 relative uncertainty  $\Delta \varepsilon / \varepsilon$  of 7% for the pixel efficiency at 378 nm. With a large 545 number of packets used in the analysis, these selected pixels are statistically 546 sufficient for an analysis of the topics of interest. It is worth mentioning that the 547 pixel efficiencies remained constant at a level of  $\pm 11\%$  as of the ratios between 548 the pre- and post-flight calibrations. The check was performed for 448 subset 549 pixels [63] 550

For the selected 650 pixels, the average,  $\langle \varepsilon \rangle$ , of pixel efficiencies at 378 nm is used as a reference as follows:

$$\langle \varepsilon(378 \text{ [nm]}) \rangle = 19.3\% \pm 0.1\%.$$
 (4)

The Standard Deviation (SD) in the  $\varepsilon$ (378 [nm]) values for these pixels is ~3%, i.e., ~16% of the average  $\langle \varepsilon \rangle$  value. The N value is converted to the 'normalized count rate',  $\hat{N}$ , as follows:

$$\hat{N}_{i} = \frac{\langle \varepsilon(378 \text{ [nm]}) \rangle}{\varepsilon_{i}(378 \text{ [nm]})} \cdot N_{i}.$$
(5)

To reject temporarily unstable pixels, we define the 'active pixels' as those with a non-zero N value. Using the  $\hat{N}$  values of all the active pixels in the packet acquired at the time,  $t_m$ , the average  $\langle \hat{N} \rangle$  value is given as follows:

$$\langle \hat{N} \rangle_m = \frac{1}{(\text{Number of active pixels})} \cdot \sum_i \hat{N}_i, \text{ with } N_i \neq 0$$
 (6)

where the packet number is hereafter indicated by the subscript m. On average, ~90% of the selected pixels were active during the ToI.

#### <sup>561</sup> 4.2. The optics response model to incident directions

The EUSO-Balloon optics is optimized for the UV photons emitted from EASs, essentially a dynamic confined spot of light with a small apparent lateral spread focused on a limited area on the PDM. In general, the displacement, *d*, of the focal spot from the center of the PDM increases with the incident off-axis angle,  $\vartheta$ , from the optical axis. In this work, we evaluate the relation of these two values by using simulations of the optical system. Applying the EUSO-Balloon configuration [65], we make use of the GEANT4 module [66, 67] implemented in the  $\overline{\text{Offline}}$  framework [68].

Figure 5 displays selected examples from ray trace simulations on the cross section of the EUSO-Balloon telescope. The key configuration of the optics is indicated. The case of  $\vartheta = 4.5^{\circ}$  and  $\lambda = 365$  nm is shown here, resulting in a nominal focal point at a displacement  $d \approx 66$  mm.

At the focus, photons from a point-like source form a Point Spread 574 Function (PSF). Due to the  $\lambda$  dependence of the refractive index, chromatic 575 aberration is also prominent in the PSF. A fraction of the affected photons 576 create characteristic halos and additional structures in the PSF. Each lens can 577 occasionally cause refraction to large angles and backward reflection of photons. 578 The former introduces errors in imaging due to the photons reaching the PDM 579 away from the nominal focal point. The latter reduces the photon collection 580 efficiency. 581

<sup>582</sup> Determination of the PSF and its centroid is not trivial, particularly outside <sup>583</sup> of the  $\sim 330-400$  nm band where SNR for focusing point-like light is designed <sup>584</sup> to be maximum for EAS detections. In addition, at  $\lambda \leq 330$  nm, absorption of <sup>585</sup> photons in the PMMA lenses is significant [44, 45]. For this work, these effects <sup>586</sup> must be taken into account only in the interpretation for the absolute intensity <sup>587</sup> of diffuse light. A detailed discussion is given in Sec. 6.

<sup>588</sup> When simulating photons from various  $\vartheta$  angles on a fixed argument,  $\varphi$ , with <sup>589</sup> respect to the PDM *x*-axis, those reaching the PDM form a high density band <sup>590</sup> along the line at ~  $\varphi$ +180°. The photons incident from a given  $\vartheta$  angle mostly <sup>591</sup> contribute to the density around a particular displacement *d* on this line. The <sup>592</sup> relation between these quantities is ideally approximated by a linear function <sup>593</sup> as follows:

$$d \approx \left\langle \frac{\partial d}{\partial \vartheta} \right\rangle \cdot \vartheta, \quad \text{for } d \lesssim 82.5 \text{ mm.}$$
 (7)

594

Based on this assumption, the derivative of the relation can be determined by

	$\langle \partial d / \partial \vartheta \rangle \ [\mathrm{mm \ per \ } 1^{\circ}]$					
	$\lambda{=}330~\mathrm{nm}$	$\lambda{=}365~\mathrm{nm}$	$\lambda{=}400~\mathrm{nm}$			
$\varphi'=\pm 0^\circ$	$14.20\pm0.08$	$15.01\pm0.03$	$14.73\pm0.03$			
$\varphi'=\pm15^\circ$	$14.29\pm0.08$	$15.00\pm0.03$	$14.70\pm0.02$			
$\varphi'=\pm30^\circ$	$14.29\pm0.07$	$15.00\pm0.02$	$14.72\pm0.02$			
$\varphi' = \pm 45^{\circ}$	$14.33\pm0.05$	$15.15\pm0.02$	$14.80\pm0.01$			

Table 1: Summary of the derivative  $\langle \partial d / \partial \vartheta \rangle$  by fitting simulated results for different wavelengths  $\lambda$  and incident arguments  $\varphi'$  with respect to the nearest PDM axis.

fitting simulated results. Due to the non-circular optics and optical distortion, azimuthal dependence also needs to be taken into account. The optical structure is symmetric with respect to both axes of the PDM. In this way,  $\varphi$  angles from both reference axes on the PDM are equivalent.

Table 1 summarizes the derivatives  $\langle \partial d / \partial \vartheta \rangle$  in Eq. (7) in the matrix of the wavelengths  $\lambda$  and arguments  $\varphi'$  with respect to the nearest PDM axis. The second terms indicate the uncertainty in fitting.

In this work, we use a representative value of the derivative in Eq. (7) as follows:

$$\left\langle \frac{\partial d}{\partial \vartheta} \right\rangle \equiv 14.6 \text{ mm per } 1^{\circ}.$$
 (8)

We apply this equation to all parts of the PDM. Within the simulated combinations, this value has a maximum uncertainty of  $\sim \pm 0.6$  mm per 1°, on the order of  $\sim 4\%$  to Eq. (8).

According to Eqs. (7) and (8), we assign a nominal direction seen by each pixel at its center position (x, y) represented by  $\vartheta$  and  $\varphi$  angles as follows:

$$\begin{pmatrix} x_i \\ y_i \end{pmatrix} \cong -\left\langle \frac{\partial d}{\partial \vartheta} \right\rangle \cdot \vartheta_i \cdot \begin{pmatrix} \cos \varphi_i \\ \sin \varphi_i \end{pmatrix}. \tag{9}$$

As seen in Fig. 5, the PSF may extend beyond the size of a pixel. A certain fraction of the photons on the pixel are not from the nominal FoV of that pixel. The inverse function of Eq. (9) can thus only deduce a likely incident direction of each photon reaching the PDM. The reciprocal of the derivative  $\langle \partial d/\partial \vartheta \rangle$  is equivalent to 'plate scale.' The nominal angle of view,  $\alpha_{\text{pix}}$ , seen by each pixel is  $\approx 0.20^{\circ} (= 2.88 \text{ [mm]}/14.6 \text{ [mm per 1°]})$ . Along the PDM axis, considering  $\pm 3 \text{ MAPMTs}$  yields an equivalent dimension of  $\pm 82.5 \text{ mm} (= \pm 3 \times 27.5 \text{mm})$  as seen in Fig. 4. By doubling the  $\vartheta$  value in Eq. (7) to match d = 82.5 mm, the nominal angle of view,  $\alpha_{\text{PDM}}$ , of the PDM is defined as follows:

$$\alpha_{\rm PDM} \approx 2 \cdot \left(\frac{82.5 \; [\rm mm]}{14.6 \; [\rm mm \; per \; 1^{\circ}]}\right) = 11.3^{\circ}.$$
(10)

<sup>619</sup> As a reference, the corresponding length,  $L_{\rm PDM}$ , projected on the level of <sup>620</sup>  $h_0 \ll H_0$  is given by:

$$L_{\rm PDM} \sim 2 \left( H_0 - h_0 \right) \cdot \tan \left( \frac{\alpha_{\rm PDM}}{2} \right) \approx 7.5 \, [\rm km] \cdot \left( \frac{H_0}{38 \, [\rm km]} \right). \tag{11}$$

#### 621 4.3. Imaging the normalized count rates on geographic coordinates

To describe the incident direction of photons, we define a polar coordinate system by the nadir angle,  $\Theta$ , and the azimuth,  $\Phi$ , at the EUSO-Balloon telescope. We assume that the position of the telescope is above the GPS ground track of the optical axis, displayed in Fig 1.

To correlate assigned direction to the pixel, the corresponding incident direction can be expressed as follows:

$$\vartheta \equiv \Theta \tag{12a}$$

$$\varphi \equiv \Phi - \Phi_0(t), \tag{12b}$$

by taking into account the orientation  $\Phi_0$  of the telescope as shown in Fig. 3.

Figure 6 illustrates the key geometry used in the analysis. Definitions of key points and coordinate systems are labeled.

To image the normalized count rates  $\hat{N}$  plotted on geographic coordinates, we assume that the count rate in each pixel is purely due to the photons incident from the assigned nominal direction. In addition to those emitted in this direction, photons may have been scattered, e.g. by clouds in the line of sight. We map the distribution according to Point  $G(X, Y, h_0)$  independent of local elevation. Assuming that the Earth is a globe with a radius  $R_{\oplus}$ , the distance, r, of Line Segment  $\overline{\text{GE}}$  can be expressed using the cosine theorem as follows:

$$r = (R_{\oplus} + H_0) \cdot \cos \Theta$$
  
-  $\sqrt{(R_{\oplus} + h_0)^2 - (R_{\oplus} + H_0)^2 \cdot (1 - \cos^2 \Theta)}$  (13a)

$$\approx \frac{H_0 - h_0}{\cos \Theta}.$$
(13b)

Equation (13a) is important for similar analyses with data acquired by satellite-based missions with much wider FoV telescopes.

In this work, we use Eq. (13b) as the effect of the Earth's curvature is small for  $L_{\text{PDM}} \ll R_{\oplus}$  or/and  $H_0 \ll R_{\oplus}$ . Point G (X, Y, Z) is given by:

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} r \cdot \sin \Theta \sin \Phi \\ r \cdot \sin \Theta \cos \Phi \\ h_0 \end{pmatrix}.$$
 (14)

Using the GPS data of the ground position of the optical axis at Point O', geographic coordinates in radians at Point G are located to as follows:

$$(\text{Lat.}) = \frac{Y}{R_{\oplus} + h_0} + (\text{Lat. at Point O'})$$
(15a)

$$(\text{Long.}) = \frac{X}{(R_{\oplus} + h_0) \cdot \cos(\text{Lat.})} + (\text{Long. at Point O'}).$$
(15b)

To analyze the geographic distribution of  $\hat{N}$  values defined by Eq. (5), the RoI is treated as a grid with a separation of 1.8" in geographic coordinates which corresponds to ~37 m for the east-west X- and ~56 m for the north-south Ydirections. With a ~130 m (=  $\alpha_{pix} \cdot H_0$ ) square projected area per pixel, it may be shared by up to twelve grid points for  $H_0 = 38$  km.

The  $\hat{N}$  value of every active pixel and packet is filled to any grid point within the projected pixel area. As a function of the packet time  $t_m$ , the combinations of the *i*-th pixel and the *k*-th grid point are indicated as follows:

$$\delta_{i,k}(t_m) = \begin{cases} 1, & \text{overlapping} \\ 0, & \text{otherwise,} \end{cases}$$
(16)

where the grid point number is hereafter denoted by the subscript k. Using all the available data, the average,  $\langle \tilde{N} \rangle$ , of the  $\hat{N}$  values projected on the grid point is evaluated by using all involved packets as follows:

$$\left\langle \tilde{N} \right\rangle_{k} = \frac{\sum_{m} \sum_{i} \left[ \delta_{i,k}(t_{m}) \cdot \hat{N}_{i}(t_{m}) \right]}{\sum_{m} \sum_{i} \delta_{i,k}(t_{m})}.$$
(17)

The total number of grid points, K, is  $3.8 \times 10^5$ , where at least one packet is used to determine the  $\langle \tilde{N} \rangle$  values. For the discussion in Sec. 6, we also make use of data with a coarser grid separation.

#### 647 5. Results

#### <sup>648</sup> 5.1. The time evolution of the normalized count rates

In this section, we present two main results from the primary analyses described in Sec. 4. The first is the time evolution of the normalized count rates and the second is their distribution projected onto geographic coordinates. The statistical errors and uncertainties derived from additional factors are also estimated. Due to the selection criterion imposed on the pixels, the normalized count rates have a relative uncertainty of 7% in pixel efficiencies. The detailed discussion and interpretation are given in Sec. 6.

Figure 7 displays the average normalized count rates  $\langle \hat{N} \rangle$  defined by Eq. (6) as a function of the packet time  $t_m$ . Data are partly eliminated due to a temporary hardware problem at 04:17 and due to a transient instability of the electronics around 04:58 and 05:07 resulting in high count rates in a few specific MAPMTs [26]. Interruptions starting at 03:47 and 05:13 were due to the system checks.

In the time interval between 04:38 and 04:52, referred to as Case (a), when the  $\langle \hat{N} \rangle$  values are low and stable, the average  $\langle N \rangle$  values are evaluated by several times 10<sup>4</sup> independent samples from the active pixels. In typical packets in Case (a), all or almost of all 650 selected pixels were active and the statistical error is irrelevant. The relative SD,  $\hat{\sigma}/\langle \hat{N} \rangle$ , among these pixels is on the order of  $\sim 15\%$ . This deviation includes the non-uniform response of the optics to diffuse light and possible non-uniform light distribution in the FoV.

When this is not the case, and  $\langle \hat{N} \rangle$  values are relatively high in particular 669 during the early part of the ToI, their deviation among pixels is large due to the 670 light source distribution inside the observation area as expected in Fig. 1. In 671 this time interval, the number of active pixels frequently varies. The definition 672 of normalized count rates by Eq. (2) may introduce a systematic uncertainty 673 on the  $\langle \hat{N} \rangle$  values due to the pile-up effect in response to high intensity light 674 sources. Around 03:15, such a case is found. The  $\langle \hat{N} \rangle$  value is suppressed in 675 this case. 676

After 03:21, flasher and laser events were generated inside the observation 677 area of the EUSO-Balloon telescope. Although no synchronization was made 678 with the EUSO-Balloon telescope, signals from such events were observed and 679 recognized in a few hundred packets by a specific analysis [26, 59]. These packets 680 are included in the analyzed data. At the flight altitude of the helicopter, the 681 corresponding length to the diagonal of the nominal FoV is  $\sim 10$  km. Any laser 682 event thus does not exceed  $\sim$ 32 µs, i.e., it takes at most 13 samples to cross this 683 length at the speed of light. In this way, the impact on the displayed results is 684 negligible. 685

#### <sup>686</sup> 5.2. The normalized count rates projected onto geographic coordinates

Figure 8 displays the average normalized count rates  $\langle \tilde{N} \rangle$  on grid points defined by Eq. (17) projected onto geographic coordinates. The shaded area represents the area for which there are no determined  $\langle \tilde{N} \rangle$  values.

The uncertainties in  $\langle \tilde{N} \rangle$  value are correlated with that of location. Bad assignment of the nominal direction seen by each pixel introduces an artificial fluctuation into Eq. (17). In the following, the maximum uncertainty in location, in terms of misplacement from the position given by Eqs. (15a) and (15b), is estimated for the float altitude  $H_0 = 38$  km. Unless otherwise mentioned, they are intended to represent the positions seen at the corners of the nominal FoV. The statistical error of the  $\langle \tilde{N} \rangle$  values primarily depends on the number, <sup>697</sup>  $\sum_{m} \sum_{i} \delta_{i}(t_{m})$ , of measured packets per grid point. It can be up to 130 packets <sup>698</sup> with an average of ~12. In general, the grid points near the boundary area have <sup>699</sup> a few packets used.

For the grid points where more than one packet is used, the *corrected sample* standard deviation,  $\tilde{\sigma}$ , can be calculated. With respect to the  $\langle \tilde{N} \rangle$  values given by Eq. (17), the relative SDs,  $\tilde{\sigma}/\langle \tilde{N} \rangle$ , from  $3.6 \times 10^5$  grid points are distributed with the mean value of ~23%. For this grid resolution, the mean of the relative errors to the average  $\langle \tilde{N} \rangle$  values is ~13%.

At the typical ground speed  $\langle v_0 \rangle$ , EUSO-Balloon traversed the  $L_{\rm PDM}$  length corresponding to the nominal angle of view  $\alpha_{\rm PDM}$  for a duration of around 15 min ( $\sim L_{\rm PDM}/\langle v_0 \rangle$ ). The motion and rotation of the EUSO-Balloon telescope could lead to a difference in time between the first and last measured packets of up to ~40 min. The local time of the ToI was 23:08–01:48. Particularly in the populated zone, variability due to human activities cannot be ruled out.

The PSF intrinsically introduces errors in location. Due to the dependence on the wavelength and incident direction of photons, the relevant errors cannot be uniquely formulated. Deduced from a compact hotspot seen in Example (i) of Fig. 4, such errors are supposed to be relatively small, compared with those introduced by the analysis process. An additional discussion of these errors is given in Sec. 6.

Since we assume the  $\alpha_{\text{PDM}}$  angle, using Eqs. (7) and (8), the maximum uncertainty of ~4% from these equations is propagated to the uncertainty,  $\Delta \vartheta$ , in assigned pixel direction, which can be up to  $\approx 0.4^{\circ}$  (= 4% ·  $\alpha_{\text{PDM}}/\sqrt{2}$ ). In this way, the location of the grid points has an associated uncertainty,  $H_0 \cdot \Delta \vartheta$ , of up to ~160 m.

In the region where the  $\langle \tilde{N} \rangle$  values are determined, the elevations of the terrain range between 205 m and 410 m according to Ref. [69]. Thus their deviations,  $\Delta h$ , from the reference  $h_0 = 296$  m are smaller than 120 m. The uncertainty,  $\Delta h \cdot \alpha_{\rm PDM}/\sqrt{2}$ , in location is less than ~20 m.

During the flight, the alignment of the MAPMTs on the PDM might differ

from what was designed by up to  $\sim 1 \text{ mm}$  in the form of gaps between neighboring BG3 filters. Such a misplacement could introduce an error in the assigned direction by the order of  $\sim 0.07^{\circ}$  (= 1 [mm] / 14.6 [mm per 1°]) resulting in a  $\sim 50$  m uncertainty in the projected position in the whole observation area.

Particularly in the beginning of the ToI, large torsion was loaded resulting in rapid rotation and oscillation of the EUSO-Balloon telescope. Such effects were mitigated in the western part of the RoI. Uncertainties in the location of the grid points by using Eqs. (12a) - (15b) effectively increase the apparent size of the point-like sources. This results in broadening hotspots, as seen in the eastern part of the RoI.

During the ToI, the orientation of the EUSO-Balloon telescope was monitored every 1 s. Thus the maximum uncertainty,  $\Delta \Phi_0$ , of the orientation is ~7° from its maximum angular velocity. It was the case in the early part of the ToI and in the eastern part of the RoI. This leads to the maximum error,  $(L_{\rm PDM}/\sqrt{2}) \cdot \Delta \Phi_0$ , in location to be ~650 m. This effect then decreases with the time as rotation and oscillation damped during the flight in the ToI.

# 743 6. Discussion

In this section, we discuss the results of the EUSO-Balloon data from three aspects; imaging capability by comparing correlations between the measured count rates and ground-based sources mainly to validate the analysis method in use, discussions on the role of count rates in exposure for UHECR observations and the absolute intensity of diffuse light. The outlook for the further pathfinder missions follows.

Correlation between the normalized count rate distribution and
 ground-based sources

In Fig. 8, several hotspots and extended light sources in the Timmins area and structures in the Montcalm Mine area are clearly visible. In order to compare with a light source distribution mainly in the visible band, we use the DMSP data shown in Fig. 1. To identify the counterparts to the hotspots, we utilize public online map services [69, 70] and Landsat Imagery [71].

Figure 9 displays an extract of the Timmins area from Fig. 8 with VDN contours of the DMSP data, as in Fig. 1. The scales and resolutions have been modified. The following labels are given to the areas of the local VDN maxima with their values in superscripts: Hoyle Mine (H), Bell Creek Mine (B), north shore of Porcupine Lake (P), downtown of Timmins (T), airport (A) and shore of Kamiskotia Lake (K). The inset shows the Montcalm Mine area (M) in the western part of the RoI.

Even with the different spatial resolutions, generic patterns of the normalized count rates  $\langle \tilde{N} \rangle$  as seen in the RoI are in good agreement with the distribution of the visible light fluxes in the DMSP data. Except for Area (K), the hotspots are found in the areas of the local VDN maxima. Multiple hotspots can be easily recognized in Areas (H), (P) and (M).

In order to find the correlation with the known light sources, we define the hotspots as spatially confined zones with high  $\langle \tilde{N} \rangle$  values. To avoid the selection of hotspots that are purely due to fluctuations, a cut of 120 pe  $\text{GTU}^{-1}$  is set on the sum of the  $\langle \tilde{N} \rangle$  values of 24 (= 6 × 4) grid points, i.e., an average value of  $\langle \tilde{N} \rangle > 5$  pe pixel<sup>-1</sup>  $\text{GTU}^{-1}$ . The grid separation in this discussion corresponds to a ~220 m on both coordinates.

Table 2 summarizes the 16 selected hotspots. Key measured values,
the ground-based counterpart sources and general remarks on the hotspots
are described therein. The presented counterpart sources are found using
Refs. [69, 70, 72].

For each hotspot, the maximum  $\langle \tilde{N} \rangle$  grid point is likely to be correlated with its counterpart source. Hotspot (X1) is found in the area without a local VDN maximum. It coincides with the position of a mining ground at Pamour. In UHECR observations, good accuracy in location is an essential requirement for the analysis of EAS events. The capability of finding temporary intense sources or ones not shown on the map also helps eliminate the fraction of the observation area.

Table 2: Summary of the 16 selected hotspots. The labels are given according to the areas of the VDN maxima in Fig. 9, except for Hotspot (X1). Using Refs. [69, 70, 72], counterpart sources for the maximum  $\langle \tilde{N} \rangle$  grid points are given along with general remarks on the hotspots.

T . h . l	Nearest	st Maximum $\langle \tilde{N} \rangle$ grid point			Ctratab	Counterparts to maximum $\langle \tilde{N} \rangle$ grid point	
Label	time	Lat.	long.	$\langle \tilde{N} \rangle$	Stretch	(Remarks for the whole hotspot)	
(H1)	03:08	$48^\circ 32' 57'' \mathrm{N}$	$81^\circ03'19''\mathrm{W}$	12	0.1	Industrial facility (boundary)	
(H2)	03:08	$48^\circ 32' 54'' \mathrm{N}$	$81^\circ04'22''\mathrm{W}$	23	1.4	Industrial complex with railroad yard, power plant etc.	
(H3)	03:08	$48^\circ 32' 57'' \mathrm{N}$	$81^\circ06'30''\mathrm{W}$	25	2.3	Mine pit (resolved into two pits ${\sim}1~{\rm km}$ apart)	
(H4)	03:08	$48^\circ 33' 57'' \mathrm{N}$	$81^\circ06'42''\mathrm{W}$	29	1.2	Mine pond	
(X1)	03:09	$48^\circ 30' 55'' \mathrm{N}$	$81^\circ06'48''\mathrm{W}$	11	0.2	Mine pit (no corresponding VDN maximum)	
(B1)	03:16	$48^\circ 33' 10'' \mathrm{N}$	$81^\circ10'47''\mathrm{W}$	62	2.2	Mining ground	
(P1)	03:22	$48^\circ 28' 58'' \mathrm{N}$	$81^\circ12'19''\mathrm{W}$	21	8.5	South Porcupine community (also resolved to Pottsville and	
						Porcupine at $\sim$ 2–3 km to the east)	
(P2)	03:30	$48^\circ 28' 13'' \mathrm{N}$	$81^\circ14'02''\mathrm{W}$	31	0.5	Mining ground (boundary)	
(P3)	03:31	$48^\circ 27' 59'' \mathrm{N}$	$81^\circ14'52''\mathrm{W}$	23	0.2	Mine pit (boundary)	
(T1)	03:34	$48^\circ 29^\prime 39^{\prime\prime} \mathrm{N}$	$81^\circ 16' 54'' \mathrm{W}$	6.3	0.3	Mining ground	
(T2)	03:36	$48^\circ 32' 21'' \mathrm{N}$	$81^\circ 17' 23'' \mathrm{W}$	9.4	0.6	Cement factory	
(T3)	03:37	$48^\circ 28' 33'' \mathrm{N}$	$81^\circ19'15''\mathrm{W}$	29	27	Park on a residential zone boundary. Commercial facility and	
						high $\langle \tilde{N} \rangle$ zones	
(T4)	03:42	$48^\circ 29' 34'' \mathrm{N}$	$81^\circ21'28''W$	20	0.5	Industrial plant on the bank of Mattagami River	
(A1)	03:46	$48^\circ 33' 55'' \mathrm{N}$	$81^\circ 22' 13'' \mathrm{W}$	16	0.1	Airport parking lot (boundary)	
(M1)	05:30	$48^\circ 40'00''\mathrm{N}$	$82^\circ05'45''W$	11	0.4	Mining ground	
(M2)	05:30	$48^\circ 40' 26'' \mathrm{N}$	$82^\circ05'56''\mathrm{W}$	11	0.1	Facility $\sim 0.9~{\rm km}$ from the counterpart of Hotspot (M1)	

Nearest time indicates for the closest approach to the maximum  $\langle \tilde{N} \rangle$  grid point and EUSO-Balloon.

 $\langle \tilde{N} \rangle$  values are given in units of pe pixel<sup>-1</sup> GTU<sup>-1</sup>. The stretch of the confined hotspot area is indicated in units of km<sup>2</sup>. Hotspots (H1), (P2), (P3) and (A1) are measured near the boundary of the nominal FoV with a limited number of packets.

<sup>786</sup> In the following, we discuss some of the characteristic hotspots and their

<sup>787</sup> counterparts. Additionally, lower  $\langle \tilde{N} \rangle$  values are found in some areas which <sup>788</sup> contain potential light sources. Possible interpretations for such cases are also

- 789 given.
- <sup>790</sup> In Example (i) of Fig. 4, Hotspot (H1) is recognized in the bottom-right

<sup>791</sup> MAPMT. Hotspot (X1) is in the upper part of the PDM. In the same example,

<sup>792</sup> Hotspots (H2) and (H3) are clearly identified. Hotspot (H4) is on the bottom

<sup>793</sup> edge.

Hotspot (H1) illustrates a typical PSF for the photons from a compact source with a scale of 50–100 m. It spreads over  $\sim 3 \times 3$  pixels, which corresponds to  $\sim 0.6^{\circ}$ . The extent of the hotspots seen in Figs. 8 and 9 is broadened by uncertainties derived from the analysis. In the case of intense light sources, the breadth of such images is also affected by the photons that are scattered by molecules in the atmosphere. This effect was also observed and recognized in the events from the LED and xenon flashers on the helicopter.

Before ~04:00, several hotspots contribute to the large variations of the  $\langle \hat{N} \rangle$  value seen in Fig. 7. Distinctly high values are found around 03:14-03:16. Apart from this, contributions from the individual hotspots are not distinguished early in the ToI. This behavior can be explained by the passage of Hotspot (B1) in the nominal FoV for a short interval. This hotspot contains the data with saturated count rates. Thus the  $\langle \tilde{N} \rangle$  values shown in Table 2 represent the lower limits.

Moving forward in time through the ToI, the  $\langle \hat{N} \rangle$  values then gradually decrease as seen in Fig. 7. The gradient of the  $\langle \tilde{N} \rangle$  values with the distance from Area (A) is seen in Fig. 8. Such behavior extends even beyond the boundary of the non-zero-VDN area, possibly due to the presence of clouds in the FoV. The pilot of the helicopter reported such conditions between 04:07 and 04:19 by looking up at the sky.

Hotspot (T3) is the largest of the listed hotspots, in terms of its extent. It extends in a populated zone and continues into the neighboring forestry zones. Inside this hotspot, there are a few potential counterpart sources to the grid points which have locally high  $\langle \tilde{N} \rangle$  values.

In contrast, relatively low  $\langle N \rangle$  values are observed over the populated zone around the VDN maximum of Area (T). A possible interpretation is an unstable behavior of the PDM that decreases the number of active pixels. Such situations tended to occur where a large number of photoelectrons were generated in a broad part of the PDM. As for the impact of this effect on UHECR observations, detections of EASs are primarily suppressed in such an area with too intense light and only determination of the affected area is relevant. In the upgraded electronics, such a problem has been overcome and a dynamic range of photon counting has been extended to a few hundred photoelectrons [73].

In Fig. 9, no clear hotspot appears in the  $\langle \tilde{N} \rangle$  distribution near Area (K) 827 where there are potential artificial light sources on the shore and at a nearby 828 mining ground [69]. A possible explanation is that the VDN values in this area 829 are no higher than 7 which is barely above the sensitivity of the DMSP data in 830 the RoI. Thus, the  $\langle \hat{N} \rangle$  values measured in this area may not have significant 831 increases, particularly under possible cloudy conditions. As also seen in Fig. 7, 832 data acquisition was interrupted at 04:17 when EUSO-Balloon flew above this 833 area and the data amount contributes less to the  $\langle \tilde{N} \rangle$  distribution. 834

In Area (M) in Figs. 8 and 9, there are Hotspots (M1) and (M2). The corresponding peaks are observed around 05:30 in Fig. 7. The maximum  $\langle \tilde{N} \rangle$ grid point of Hotspot (M2) is ~150–250 m away from the counterpart [72], which shows the location uncertainty in this part of the RoI.

At ~05:44, additional peaks are found in Fig. 7. At that time, the potential light sources in Area (M) were well out of the nominal FoV of the EUSO-Balloon telescope. An interpretation of these peaks is that the attitude of the instrument might be affected and instantaneously pointed to the direction of Hotspots (M1) and (M2). The GPS data show a significant impulsive acceleration,  $\ddot{H}_0$ , of >2 m s<sup>-2</sup> in the vertical direction in comparison to its root mean square  $\sqrt{\langle \ddot{H}_0^2 \rangle} \sim 0.5 \text{ m s}^{-2}$  over the ToI.

# 846 6.2. Implications for space-based UHECR observations

In previous work reported in this Journal [22], the scientific performance of the JEM-EUSO instrument and its expected exposure to UHECR observations have been discussed. For the baseline design of JEM-EUSO, thresholds for the trigger algorithms are set by the average count rates,  $\bar{N}$ , from diffuse light. They are dynamically applied first on the pixel level and then on the higher level of the PDM segment either on MAPMTs or ECs [26, 27].

In the aforementioned work, it was assumed that the effect from the Moon is the main component of the temporal  $\bar{N}$  variation in the orbit. The impact from the local light component, especially artificial light, was separately evaluated by analyzing the distribution of visible light fluxes from the DMSP data. These distributions were used to evaluate two parameters: the observational duty cycle,  $\eta$ , and the fraction,  $f_{\rm loc}$ , of the area with intense local light sources.

The  $\eta$  value was given as a ratio of the observation time,  $T_{\rm obs}$ , to the whole mission lifetime,  $T_0$ . The  $T_{\rm obs}$  time is defined as the time when the trigger algorithms are operational. For instance, time under daylight, twilight and large moonlight has been eliminated.

The  $f_{loc}$  value was given as an average ratio of the area with intense light sources to the whole area covered by the ISS orbit. It represents the expected fraction within the instantaneous observation area that is partly or totally lost due to such sources, including cities, lightning, aurorae etc.

The results of the EUSO-Balloon mission allow for similar studies, but with real data, i.e., the  $\langle \hat{N} \rangle$  distribution from Eq. (6) and the  $\langle \tilde{N} \rangle$  distribution from Eq. (17). The data from this work cover a ~2.5 hour time interval and a ~780 km<sup>2</sup> area and thus the given distributions represent the particular case of the EUSO-Balloon flight. This time and area are small compared with those potentially achieved by space-based missions, i.e., several years of mission lifetime and an order of 10<sup>8</sup> km<sup>2</sup> area on the Earth.

Figure 10 displays the temporal  $\langle \hat{N} \rangle$  distribution in terms of the packets as shown in Fig. 7. The histogram denotes the fraction of packets relative to the total number of packets,  $M = 1.5 \times 10^5$ . The unity of the distribution is normalized to the ~2.5 hours of the time assigned for this work. The dashed curve shows the cumulative fraction above the given  $\langle \hat{N} \rangle$  value.

In a large fraction of the ToI, the distribution contains not only diffuse light but also the artificial light sources. The time intervals when the nominal FoV was free from the influence of the local light sources are limited. The peak value of the distribution coincides with the typical  $\langle \hat{N} \rangle$  value in Case (a).

Although the trigger algorithms need to consider further effects such as different pixel efficiencies [26], the average normalized count rates are used for a first order discussion. In practice, the  $\eta$  value is determined by the permissible limit,  $\bar{N}_{\text{lim}}$ , of the average count rate which allows the trigger algorithms to be operational and is expressed as follows:

$$\eta\left(<\bar{N}_{\rm lim}\right) \equiv \frac{T_{\rm obs}}{T_0} = \frac{1}{T_0} \cdot \int_0^{\bar{N}_{\rm lim}} \frac{dT}{d\bar{N}} \, d\bar{N}.\tag{18}$$

where  $dT/d\bar{N}$  denotes the temporal  $\bar{N}$  distribution in the mission lifetime. The histogram shown in Fig. 10 gives such a distribution in the ToI of the EUSO-Balloon flight. The cumulative fraction shown in Fig. 10 represents Eq. (18). The time intervals when the data were eliminated in Fig. 7 are excluded. The time between triggers is included as the time that the instrument was operational. In the real space-based mission, the trigger rate is far smaller and the count rates are only monitored for trigger algorithms.

For space-based observations, the main scientific outputs will be the energy spectrum and arrival direction distribution of UHECRs. Both require determination of the exposure, A, for UHECR observations. This should be described as a function of the energy  $E_0$  and should be projected onto the celestial sphere with the orbit taken into account.

Under moonless, clear atmosphere conditions in dark areas presumably without the effect of artificial light, a reference count rate,  $N_0$ , is defined as the average of the  $\bar{N}$  values from diffuse light. For such conditions, a reference function of the instantaneous aperture,  $\dot{A}_0$ , for UHECR observations is obtained by simulating a large number of EASs and the instrument response. The instantaneous aperture,  $\dot{A}$ , for different conditions of the diffuse light empirically scales by the  $\bar{N}$  value as follows [17, 22]:

$$\dot{A}(E_0;\bar{N}) = \dot{A}_0 \left( \sqrt{\frac{N_0}{\bar{N}}} \cdot E_0 \right)$$
(19)

<sup>907</sup> in units of km<sup>2</sup> sr. Here, the effects of clouds and the local light component <sup>908</sup> have been omitted.

The  $\overline{N}$  value is variable as a function of the time, T, in the mission lifetime. By integrating Eq. (19), the exposure for UHECR observations is given as a function of the energy as follows:

$$A(E_0) \equiv \int_0^{T_0} \dot{A} \left( E_0, \bar{N}(T) \right) \, dT$$
 (20a)

$$= \int_{0}^{\bar{N}_{\text{lim}}} \left[ \dot{A}_0 \left( \sqrt{\frac{N_0}{\bar{N}}} \cdot E_0 \right) \cdot \left( \frac{dT}{d\bar{N}} \right) \right] d\bar{N}.$$
(20b)

<sup>909</sup> in units of km<sup>2</sup> sr yr. Here  $\dot{A} = 0$  for the time intervals when no UHECR <sup>910</sup> observation is undertaken, including the case of  $\bar{N} > \bar{N}_{\text{lim}}$ .

For UHECRs with  $E_0 \gtrsim 10^{20}$  eV, the baseline design of JEM-EUSO has a nearly constant geometrical aperture [17, 22]. Taking into account the effects of the clouds and local light, the overall exposure at the highest energies can be expressed as:

$$A(\infty) \approx \dot{A}_0(\infty) \cdot \kappa_{\rm C} \cdot \eta \cdot (1 - f_{\rm loc}) \cdot T_0, \qquad (21)$$

where  $\kappa_{\rm C}$  is the cloud efficiency. This parameter describes the ratio of the aperture taking into account the presence of clouds to the one for clear atmosphere conditions [17, 22, 52].

Figure 11 displays the areal  $\langle \tilde{N} \rangle$  distribution in terms of the grid points as shown in Fig. 8. The clear and filled parts of the histogram indicate the fractions of the grid points with respect to the total number  $K=3.8 \times 10^5$  of grid points in the eastern and western halves, respectively. They are split at Long. 81°35′49″2W. The dashed curve shows the cumulative fraction above the given  $\langle \tilde{N} \rangle$  value.

The  $f_{\rm loc}$  value in Eq. (21) is relevant to the cumulative fraction shown in the figure. Most of the area in the western half accounts for relatively low  $\langle \tilde{N} \rangle$ values, while the eastern half is dominated by high values from the extended hotspots. It is important to recall the low  $\langle \tilde{N} \rangle$  values around Area (T) in Fig. 8. In space-based UHECR observations, the presence of such intense light sources is also foreseen. In this way, these contributions may be properly taken into account in the calculation of  $f_{\rm loc}$  values.

#### 931 6.3. The absolute intensity of diffuse light

It is primarily diffuse light that is relevant for space-based UHECR observations. Its count rate,  $\hat{N}_0$ , for clear atmosphere conditions is important for EAS analysis of the existing instrument. Although EUSO-Balloon was not expected to detect EAS events, the corresponding absolute intensity  $I_0$  could provide another reference value.

#### 937 6.3.1. The normalized count rates under clear atmosphere conditions

As the reflectivity of the clouds is higher, the time interval and area with lowest count rates are considered to represent a case with little influence from clouds, i.e., clear atmosphere. Such conditions were present in Case (a) between 04:38 and 04:52 as mentioned in Sec. 5. At 04:36, 04:48 and 04:55, the pilot reported clear sky conditions above the helicopter.

In addition, similar conditions were considered to be present between 05:30 and 05:48 referred to as Case (b). The pilot confirmed such conditions at 05:29, 05:35 and 05:46. EUSO-Balloon was flying through and away from Area (M) as seen in Example (ii) of Fig. 4.  $\langle \hat{N} \rangle$  values are as low as in Case (a) seen in Fig. 7 if the contributions associated with Hotspots (M1) and (M2) are eliminated by strictly using 67 pixels in two MAPMTs out of the 650 selected pixels.

Figure 12 displays the  $\langle \hat{N} \rangle$  distributions for Cases (a) and (b) shown as the solid and dashed histograms, respectively. Each histogram is normalized to the total number of packets in use:  $2.3 \times 10^4$  for Case (a) and  $1.5 \times 10^4$  for Case (b). For the reference  $\hat{N}_0$  value, we quote the mode of the distribution for Case (a) obtained as follows:

$$\hat{N}_0 \approx 0.65 \text{ pe pixel}^{-1} \text{ GTU}^{-1}.$$
 (22)

The pixels used in Case (b) are a subset of those used in Case (a). The distribution for Case (b) is similar to that of Case (a) with a slightly broader fluctuation due to fewer pixels and packets in use.

#### 957 6.3.2. The optics response to diffuse light

As seen in Fig. 5, some photons from a given incident direction are occasionally detected far from the nominal focal point. They are more pronounced in diffuse light. To describe such effects, we perform a large number of ray trace simulations using the  $\overline{\text{Offline}}$  setup described in Sec. 4. Photons are isotropically incident on the optics by sampling over the area,  $S_{\text{sim}}$ , wider than the opening entrance. The maximum incident off-axis angle,  $\vartheta_{\text{lim}}$ , is set by the geometry of the baffle.

For a photon with a wavelength  $\lambda$  and incident direction given by the  $\vartheta$ and  $\varphi$  angles, let  $\beta(\lambda, \vartheta, \varphi)$  be the probability of reaching the pixel. Using ray trace simulations, the average,  $\bar{\beta}$ , for a given  $\lambda$  over the incident directions is obtained as follows:

$$\bar{\beta}_i(\lambda) \equiv \frac{1}{\Omega_{\rm sim}} \cdot \int_{\Omega} \beta_i(\lambda, \vartheta, \varphi) \, d\Omega = \frac{N_{\rm hit, i}(\lambda)}{N_{\rm sim}(\lambda)},\tag{23}$$

where  $N_{\text{hit},i}$  is the number of photons reaching the *i*-th pixel among the simulated  $N_{\text{sim}}$  photons,  $d\Omega = \sin \vartheta \, d\vartheta \, d\varphi$  is the solid angle element and  $\Omega_{\text{sim}}$  is written as follows:

$$\Omega_{\rm sim} = \int_{\Omega} \cos\vartheta \, d\Omega = \int_{0}^{2\pi} \int_{0}^{\vartheta_{\rm lim}} \left(\cos\vartheta \cdot \sin\vartheta\right) \, d\vartheta \, d\varphi. \tag{24}$$

Taking into account the pixel efficiency  $\varepsilon(\lambda)$  from Eq. (3), the 'pixel acceptance',  $\tilde{a}$ , to diffuse light can be expressed as a function of the wavelength as follows:

$$\tilde{a}_i(\lambda) \equiv \varepsilon_i(\lambda) \cdot \bar{\beta}_i(\lambda) \cdot S_{\rm sim} \cdot \Omega_{\rm sim}.$$
(25)

It has the dimensions of area multiplied by solid angle. These two qualities
cannot be decoupled due to the intrinsic PSF, absorption and scattering effects
of the Fresnel lenses.

Figure 13 displays the average pixel acceptance  $\langle \tilde{a} \rangle$  over the selected 650 pixels to diffuse light as a function of the wavelength. The shaded interval indicates the SD component,  $(\bar{\sigma}/\langle \bar{\beta} \rangle) \cdot \langle \tilde{a} \rangle$ , over these pixels due to the non-uniform optics response where  $\bar{\sigma}$  is the SD of  $\bar{\beta}$  probabilities.

Table 3: Relative abundances  $dI_0/I_0$  of photons in different wavelength bands and spectrum-weighted pixel acceptance  $\check{a}$  for the diffuse light models.

spectrum weighted pixer deceptance a for the diffuse light models.						
Model	Relative	e abundance	Spectrum-weighted			
	300 - 340	340 - 380	380 - 420	420 - 460	460 - 500	pixel acceptance $\check{a} [m^2 sr]$
Airglow	37%	39%	18%	5%	1%	$0.95\times 10^{-6}$
Starlight	15%	27%	24%	20%	15%	$0.88 \times 10^{-6}$
Light bulb	0%	1%	12%	31%	57%	$0.44 \times 10^{-6}$

The ray trace simulations of diffuse light demonstrate the non-uniform response of pixels, which cannot be simply formulated. Above 330 nm the optical system introduces an uncertainty  $\bar{\sigma}/\langle\bar{\beta}\rangle$  of ~11% to the average.

# 985 6.3.3. An interpretation for the absolute intensity estimation

<sup>986</sup> Due to the  $\lambda$  dependence of the  $\tilde{a}$  values, the model of the differential <sup>987</sup> spectrum  $dI_0/d\lambda$  of the diffuse light is needed to interpret the data. The  $I_0$ <sup>988</sup> value of diffuse light should follow the relation given by:

$$I_0 = \int_{\lambda} \frac{dI_0}{d\lambda} \, d\lambda. \tag{26}$$

In this work, the  $\lambda = 300 - 500$  nm band is chosen as a reference according to the sensitive range seen in Fig. 13.

 $_{991}$  Over this band, the spectrum-weighted pixel acceptance  $\check{a}$  is given as follows:

$$\check{a} = \frac{1}{I_0} \cdot \int_{\lambda} \left[ \langle \tilde{a}(\lambda) \rangle \cdot \frac{dI_0}{d\lambda} \right] d\lambda.$$
(27)

To determine this value, a model of the relative spectrum  $(1/I_0) \cdot (dI_0/d\lambda)$  of the diffuse light needs to be applied. In order to find a potential range of  $\check{a}$ values, we assume three spectrum models. Models of airglow and starlight are for the natural light sources. The light bulb model is for artificial sources.

Table 3 summarizes the relative abundances,  $dI_0/I_0$ , in different  $\lambda$  bands for the airglow, starlight and light bulb models together with the corresponding  $\check{a}$  value in Eq. (27). A value of unity corresponds to the intensity in the 300-500 nm band, according to Eq. (26). The airglow model is deduced from the data taken by the Ultraviolet Visual Echelle Spectrograph (UVES) [74, 75]. The starlight model is quoted from Ref. [33]. The light bulb model is from Ref .[80], intended for a lower bound of the  $\check{a}$  value.

For the natural light source models, photons are first sampled according to these models. Using the Monte Carlo method by the 'libRatran' code [76, 77], these photons are then traced from the top of the atmosphere and the back-scattering in the atmosphere is simulated to obtain their spectra on the telescope at 38 km asl.

The airglow emission has a continuum spectrum characterized by prominent lines in the 300–400 nm band. Its back-scattered light also shows a dominant abundance for short  $\lambda$ . The back-scattered starlight has a continuum spectrum with its differential intensity rising with increasing  $\lambda$ . Another potential natural light source is zodiacal light which has a similar spectrum to the starlight model. Its contribution is considered to be very little at the local solar time of ~0 h in the ToI.

Under clear atmosphere conditions, Rayleigh scattering by molecules is the dominant process of radiation transfer [78]. For the light of extraterrestrial origin, relative abundances below  $\sim$ 320 nm are largely suppressed due to absorption by ozone molecules [79]. The response of the optics also renders contributions below  $\sim$ 300 nm negligible.

For a given  $\check{a}$  value, the expected count rate N in response to this diffuse light with a given intensity, I, is written as follows:

$$N = \check{a} \cdot I$$
(28a)  
= 0.23 [pe pixel<sup>-1</sup> GTU<sup>-1</sup>]  
 $\cdot \left(\frac{\check{a}}{10^{-6} \text{ [m}^2 \text{ sr]}}\right) \cdot \left(\frac{I}{100 \text{ [photon m}^{-2} \text{ sr}^{-1} \text{ ns}^{-1}]}\right),$ (28b)

<sup>1021</sup> for the 300-500 nm band. By substituting the measured count <sup>1022</sup> rate  $\hat{N}_0 \approx 0.65$  pe pixel<sup>-1</sup> GTU<sup>-1</sup> in Eq. (28a), the consistent  $I_0$  value is <sup>1023</sup> deduced for each model.

	$300\!-\!500~\mathrm{nm}$	$300\!-\!400~\rm{nm}$
Model (this work)	Consistent $I_0$ [pl	hoton $m^{-2} sr^{-1} ns^{-1}$ ]
Airglow	$\sim 320$	$\sim 260$
Starlight	$\sim 300$	$\sim \! 170$
Light bulb	$\sim\!640$	$\sim 30$

Table 4:  $I_0$  values deduced for different spectrum models.

Table 4 summarizes consistent  $I_0$  values in the 300-500 nm and 300-400 nm bands deduced for different spectrum models. According to abundances below 400 nm in Table 3, the intensities in the 300-400 nm band were estimated. They may be compared with former experiments [34, 35, 36].

In Case (a), the diffuse light seen by the EUSO-Balloon telescope is mostly from airglow and starlight components with an unknown mixture. Artificial light is highly unlikely to dominate the measured count rate in the forest. Thus, the values listed for artificial light would give conservative constraints. Note that airglow is a dynamic phenomenon. Its intensity varies in time and geographic position as well as by the influence of geomagnetic activity and atmospheric tides [81]. These variations could even exceed these model dependences.

A possible lower limit may be inferred with a virtual ideal instrument by assuming that all the photons incident on the optics aperture would focus on the nominal angle of view  $\alpha_{\text{pix}}$  of a pixel. As the pixel efficiency  $\langle \varepsilon \rangle$  is maximum at ~378 nm, the maximum possible pixel acceptance for such an instrument is given by  $\langle \varepsilon(378 \text{ [nm]}) \rangle \cdot S_{\text{opt}} \cdot (\alpha_{\text{pix}})^2$  and is  $2.2 \times 10^{-6} \text{ m}^2$  sr. Applying it to Eq. (28b) yields ~130 photons m<sup>-2</sup> sr<sup>-1</sup> ns<sup>-1</sup> to the reference count rate  $\hat{N}_0$  in Eq. (22).

With the assumed optics response model, further uncertainty in the  $\check{a}$ values may be derived from the response of the EUSO-Balloon instrument. By taking into account the 7% uncertainty  $\Delta \varepsilon / \varepsilon$  in pixel efficiencies from the PDM calibration and the pixel acceptance dependence of ~11%, the overall uncertainty is ~13%  $\left(=\sqrt{(\Delta \varepsilon / \varepsilon)^2 + (\bar{\sigma} / \langle \bar{\beta} \rangle)^2}\right)$ . Although not all selected 650 pixels gave pre-flight calibration, the selection of pixels allows  $\pm 11\%$ level uncertainty of a possible variation of the pixel efficiency during the flight. As mentioned in Sec. 5, the relative SD in normalized count rates among pixels is ~15% during the Case (a) time interval and thus it is consistent with the hypothesis of illumination of uniform diffuse light within the uncertainty of ~18%  $\left(=\sqrt{(13\%)^2 + (11\%)^2}\right)$ .

# 1053 6.4. Outlook

The experimental studies on UV light as background continue through 1054 further pathfinder missions. A flight of EUSO-SPB using NASA's 1055 Super-Pressure Balloon (SPB) [82] was made over the South Pacific between 1056 April 24 and May 7, 2017 UTC [83]. On-ground tests and preparations of 1057 Mini-EUSO [84] are in progress with a possibility to be operated in 2019. A 1058 ground-based pathfinder experiment EUSO-TA [85] has been operated at the 1059 site of the TA experiment in Utah, USA. It is capable of measuring the night 1060 sky background, including direct airglow emission. 1061

EUSO-SPB introduced and flew with upgraded subsystems relative to 1062 EUSO-Balloon, which solved some of the issues seen in the instrument. PSF 1063 was also improved that allowed better imaging capability, while most of the 1064 time it flew above the pattern-less ocean. EUSO-SPB had an autonomous 1065 trigger for EAS events that had been proven by the UV lasers at the site of the 1066 TA experiment. The operation of EUSO-SPB was undertaken from NASA's 1067 Mid-Latitude Super Pressure Balloon Launch Site at Wanaka Airport, New 1068 Zealand. It was terminated due to a gas leakage of the balloon envelope. As 1069 much data as possible were downlinked before the instrument was abandoned 1070  $\sim 200$  nautical miles south-east of Easter Island. 1071

Thanks to the trigger system, EUSO-SPB had the potential to detect a few EAS events if it had flown as long as a few months achieved in the former SPB flights. The observable energy range of the cosmic rays was lowered to a few times 10<sup>18</sup> eV. The data analysis of EUSO-SPB, more oriented to EAS detections and estimation of the exposure to cosmic rays as discussed in Sec. 6.2 1077 is underway.

Mini-EUSO is a 25 cm telescope with a refractive Fresnel optics mounted on the UV-transparent, nadir-facing window of the Russian module Zvezda on the ISS. With one PDM, it is designed to observe a 44° square FoV, corresponding to a square of side ~300 km on the Earth's surface. Orbiting above the airglow layer, Mini-EUSO is capable of measuring the sum of direct and indirect components of diffuse light. The ISS orbit that ranges within latitudes of  $\pm 51.6^{\circ}$ allows for the measurements at various positions over the Earth.

It is expected to provide interesting data on UV-luminous phenomena in the upper atmosphere [86]. For example, it will be possible to achieve more detailed information on airglow emissions, in particular, variation over time and position on the Earth, as well as the response to solar and geomagnetic activities. Measurements with large observation area will provide an opportunity to investigate different scale phenomena in airglow science such as the effect of the atmospheric gravity wave [87].

# 1092 7. Conclusions

The EUSO-Balloon mission was designed, constructed and flown operating a  $\sim 1 \text{ m}^2$  refractive Fresnel optics and a prototype PDM. Towards space-based UHECR observations, it was the first pathfinder mission in the JEM-EUSO program that took in-flight measurements in August 2014. After an 8 hour stratospheric flight, the instrument was safely recovered, allowing post-flight calibration in the laboratory.

In this work, we analyze  $\sim 2.5$  hours of the instrument data, in conjunction with the GPS data, post-flight PDM calibration and ray trace simulations. The main results obtained are the normalized count rates as a function of the time and their distribution on geographic coordinates over a  $\sim 780$  km<sup>2</sup> area. The high count rates with rapid variations are shown to be due to the developed area where such excesses are caused by the local artificial light sources. The lowest count rates are found when flying over forested areas. In general, the

image in the UV band is in good agreement with the distribution of the visible 1106 light fluxes measured by the DMSP satellites. By displaying the obtained 1107 image at higher resolution, more than a dozen hotspots are found and the 1108 corresponding counterpart light sources are clearly identified to ground facilities 1109 such as the airport, factories, and mines. In dark areas where EUSO-Balloon 1110 was operating under clear atmosphere conditions,  $\sim 310$  photons m<sup>-2</sup> sr<sup>-1</sup> ns<sup>-1</sup> 1111 in the 300-500 nm band is deduced to explain the measured data by the 1112 simulations and assumed diffuse light spectra. 1113

In this work, we demonstrate the imaging capability of the EUSO-Balloon 1114 telescope with wide-FoV large aperture refractive Fresnel optics. This gives 1115 new and complementary information compared with the former balloon-borne 1116 experiments that aimed at determining the absolute intensity of diffuse light. 1117 Possible impacts of diffuse light and local light to UHECR observations are 1118 discussed. The analysis methods developed can be applied to data to be 1119 obtained by the other pathfinders and real space-based missions, not only for 1120 the study of UV light as a background for UHECR observations but also to 1121 give insights on airglow science. These missions are capable of measuring and 1122 imaging a larger part of the night-Earth in the UV band. 1123

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Figure 1: GPS ground track of the EUSO-Balloon optical axis shown by the solid curve. The VDN distribution is shown in color scale. A triangle and a square mark the launch and landing positions, respectively. The hourly positions are also marked by circles. The bold curve indicates the track during the ToI. The RoI is enclosed by the dashed lines.



Figure 2: Altitude  $H_0$  of the EUSO-Balloon telescope above sea level as a function of the UTC time t. The local EDT time is shown on the top. The upper and lower arrows indicate the dark night period and the ToI, respectively.



Figure 3: Orientation  $\Phi_0$  of the EUSO-Balloon telescope as a function of the time t. The arrow represents the ToI.



Figure 4: Examples of  $\langle n \rangle$  values of all the pixels on the PDM for the packets acquired at (i) 03:09:11 and (ii) 05:47:42 on the left and right panels, respectively. Malfunctioning pixels are blackened out. The ground position of the EUSO-Balloon optical axis and the orientation of the telescope at these times are given on the top. Seen from the optics side, images are mirrored. The dimension of the PDM is shown in the right panel.



Figure 5: Selected examples of ray trace simulations for a point-like source at the incident off-axis direction  $\vartheta = 4.5^{\circ}$ . The configuration of the front (L1) and rear (L3) lenses, opening entrance (E), diaphragms (D1) and (D2) and the PDM is shown on the cross section of the EUSO-Balloon telescope. In these examples for  $\lambda = 365$  nm, the displacement  $d \approx 66$  mm from the PDM center is a nominal focal point.



Figure 6: Geometry used in the analysis. The position of the EUSO-Balloon telescope is at Point E  $(0, 0, H_0)$ . In the direction of the nadir angle  $\Theta$  and azimuth  $\Phi$ , Point G  $(X, Y, h_0)$  is defined at the distance r from Point E. Point O' indicates the position of the optical axis on  $h_0 = 296$  m asl. The orientation  $\Phi_0$  of the telescope is defined as illustrated.



Figure 7: Average normalized count rates  $\langle \hat{N} \rangle$  as a function of the packet time  $t_m$ . Data are partly eliminated due to a temporary hardware problem around 04:17 and due to a transient instability of the electronics around 04:58 and 05:07. Interruptions starting at 03:47 and 05:13 were due to a different operation mode for the system checks.



Figure 8: Normalized count rates  $\langle \tilde{N} \rangle$  projected onto geographic coordinates. The shaded areas represent the area for which there is no determined  $\langle \tilde{N} \rangle$  values. Coordinates on the corners are labeled together with ticks every 5' on both axes.



Figure 9: Extract from Fig. 8 shown with VDN contours overlaid, as in Fig. 1. The scales and resolutions have been modified. The hashed areas indicate the grid points with  $\langle \tilde{N} \rangle <$ 1.5 pe pixel<sup>-1</sup> GTU<sup>-1</sup>. Bold contours are for VDN = 4 and thin ones are given at a step of 5. The local VDN maxima are labeled with their values in superscripts: Holye Mine (H), Bell Creek Mine (B), north shore of Porcupine Lake (P), Timmins downtown (T), airport (A) and shore of Kamiskotia Lake (K). The inset shows the Montcalm Mine (M) area in the western part of the RoI.



Figure 10: Temporal  $\langle \hat{N} \rangle$  distribution in terms of the packets with respect to the total  $M = 1.5 \times 10^5$ . The unity of the distribution is normalized to the ~2.5 hour time assigned for this work. The cumulative fraction below the given  $\langle \hat{N} \rangle$  value is shown by the dashed curve to the scale on the right.



Figure 11: Areal  $\langle \tilde{N} \rangle$  distribution in terms of the grid points with respect to the total  $K = 3.8 \times 10^5$ . The contributions from eastern and western halves whose areas are even are displayed by the clear and filled parts of the histogram, respectively. The cumulative fraction above the given  $\langle \tilde{N} \rangle$  value is given by the dashed curve to the scale on the right.



Figure 12:  $\langle \hat{N} \rangle$  distributions for Case (a) of the active pixels between 04:38 and 04:52 and Case (b) of those from more strictly selected 67 pixels between 05:30 and 05:48 shown as the solid and dashed histograms, respectively. Each histogram is normalized to the total number of packets in use:  $2.3 \times 10^4$  for Case (a) and  $1.5 \times 10^4$  for Case (b).



Figure 13: Average pixel acceptance  $\langle \tilde{a} \rangle$  over the selected 650 pixels to diffuse light as a function of the wavelength  $\lambda$ . The shaded interval indicates the SD component,  $(\bar{\sigma}/\langle \bar{\beta} \rangle) \cdot \langle \tilde{a} \rangle$  over these pixels due to the non-uniform optics response.