

AperTO - Archivio Istituzionale Open Access dell'Università di Torino

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

This is the author's manuscript

Original Citation:

Availability:

This version is available <http://hdl.handle.net/2318/1699648> since 2019-04-20T16:20:59Z

Published version:

DOI:10.1016/j.astropartphys.2018.10.008

Terms of use:

Open Access

Anyone can freely access the full text of works made available as "Open Access". Works made available under a Creative Commons license can be used according to the terms and conditions of said license. Use of all other works requires consent of the right holder (author or publisher) if not exempted from copyright protection by the applicable law.

(Article begins on next page)

1 Ultra-violet imaging of the night-time earth by
2 EUISO-Balloon towards space-based ultra-high energy
3 cosmic ray observations.

4 G. Abdellaoui^h, S. Abe^{aw}, J.H. Adams Jr.^{cf}, A. Ahriche^e, D. Allard^l,
5 L. Allen^{cd}, G. Alonso^{bw}, L. Anchordoqui^{ch}, A. Anzalone^{y,u}, Y. Arai^{ay},
6 K. Asano^{ak}, R. Attallah^c, H. Attoui^a, M. Ave Pernas^{bv}, S. Bacholle^{ce},
7 M. Bakiri^a, P. Baragatti^{ae}, P. Barrillon^j, S. Bartocci^{ae}, J. Bayer^q,
8 B. Beldjilali^h, T. Belenguer^{bu}, N. Belkhalifa^a, R. Bellotti^{r,s}, A. Belov^{bp},
9 K. Belov^{cg}, K. Benmessai^a, M. Bertaina^{ab,ac}, P.L. Biermann^o,
10 S. Biktmerova^{bn}, F. Bisconti^{ab}, N. Blanc^{bz}, J. Błęcki^{bl}, S. Blin-Bondil^k,
11 P. Bobik^{br}, M. Bogomilovⁱ, E. Bozzo^{ca}, S. Briz^{cd}, A. Bruno^s, K.S. Caballero^{bh},
12 F. Cafagna^f, D. Campana^w, J-N. Capdevielle^l, F. Capel^{by}, A. Caramete^{bm},
13 L. Caramete^{bm}, P. Carlson^{by}, R. Caruso^{t,u}, M. Casolino^{az,z}, C. Cassardo^{ab,ac},
14 A. Castellina^{ab,ad}, C. Catalano^l, O. Catalano^{y,u}, A. Cellino^{ab,ad}, M. Chikawa^{ai},
15 G. Chiritoi^{bm}, M.J. Christl^{ci}, V. Connaughton^{cf}, L. Conti^{ae}, G. Cordero^{bd},
16 G. Cotto^{ab,ac}, H.J. Crawford^{cc}, R. Cremonini^{ac}, S. Csorna^{cj}, A. Cummings^{ce},
17 S. Dagoret-Campagne^j, A.J. de Castro^{cd}, C. De Donato^z, C. de la Taille^k,
18 C. De Santis^z, L. del Peral^{bv}, M. Di Martino^{ad}, A. Diaz Damian^m, T. Djemil^c,
19 I. Dutan^{bm}, A. Ebersoldt^o, T. Ebisuzaki^{az}, R. Engel^o, J. Eser^{ce}, F. Fenu^{ab,ac},
20 S. Fernández-González^{bt}, S. Ferrarese^{ab,ac}, M. Flamini^{ae}, C. Fornaro^{ae},
21 M. Fouka^b, A. Franceschi^v, S. Franchini^{bw}, C. Fuglesang^{by}, T. Fujii^{ak},
22 J. Fujimoto^{ay}, M. Fukushima^{ak}, P. Galeotti^{ab,ac}, E. García-Ortega^{bt},
23 G. Garipov^{bp}, E. Gascón^{bt}, J. Genci^{bs}, G. Giraudo^{ab}, C. González Alvarado^{bu},
24 P. Gorodetzky^l, R. Greg^{ce}, F. Guarino^{w,x}, A. Guzmán^q, Y. Hachisu^{az},
25 M. Haiduc^{bm}, B. Harlov^{bo}, A. Haungs^o, J. Hernández Carretero^{bv},
26 W. Hidber Cruz^{bd}, D. Ikeda^{ak}, N. Inoue^{at}, S. Inoue^{az}, F. Isgrò^{w,af}, Y. Itow^{aq},
27 T. Jammer^p, S. Jeong^{bc}, E. Joven^{bx}, E.G. Judd^{cc}, A. Jung^l, J. Jochum^p,
28 F. Kajino^{al}, T. Kajino^{ao}, S. Kallif^f, I. Kaneko^{az}, Y. Karadzhovⁱ,
29 J. Karczmarczyk^{bk,2}, K. Katahira^{az}, K. Kawai^{az}, Y. Kawasaki^{az,2},
30 A. Kedadra^a, H. Khales^a, B.A. Khrenov^{bp}, Jeong-Sook Kim^{ba},
31 Soon-Wook Kim^{ba}, M. Kleifges^o, P.A. Klimov^{bp}, D. Kolevⁱ, H. Krantz^{ce},
32 I. Kreykenbohm^u, J.F. Krizmanic^{ci}, K. Kudela^{br}, Y. Kurihara^{ay},
33 A. Kusenko^{ax}, E. Kuznetsov^{cf}, A. La Barbera^{y,u}, C. Lachaud^l, H. Lahmar^a,
34 F. Lakhdari^g, O. Larsson^{by}, J. Lee^{bc}, J. Licandro^{bx}, L. López Campano^{bt},
35 F. López^{cd}, M.C. Maccarone^{y,u}, S. Mackovjak^{br,1}, M. Mahdi^a, D. Maravilla^{bd},
36 L. Marcelliz^z, J.L. Marcos^{bt}, A. Marini^v, W. Marszał^{bk}, K. Martens^{ax},
37 Y. Martín^{bx}, O. Martinez^{bf}, M. Martucci^v, G. Masciantonio^z, K. Mase^{ag},

*Corresponding authors at: Institute of Experimental Physics, Slovak Academy of Sciences, Watsonova 47, 040 01 Kosice, Slovakia. Email: mackovjak@saske.sk (S. Mackovjak). Dipartimento di Fisica, Università di Torino and Istituto Nazionale di Fisica Nucleare – Sezione di Torino, Via P. Giuria 1, 10125 Turin, Italy. Email: kenji.shinozaki@to.infn.it (K. Shinozaki).

**Deceased.

38 M. Mastafa^{cf}, R. Matevⁱ, J.N. Matthews^{ck}, N. Mebarki^d, G. Medina-Tanco^{bd},
 39 M.A. Mendoza^{bg}, A. Menshikov^o, A. Merino^{bt}, J. Meseguer^{bw}, S.S. Meyer^{cd},
 40 J. Mimouni^d, H. Miyamoto^{ab,ac}, Y. Mizumoto^{ao}, A. Monaco^{r,s},
 41 J.A. Morales de los Ríos^{bv}, C. Moretto^m, S. Nagataki^{az}, S. Naitamor^b,
 42 T. Napolitano^v, R. Nava^{bd}, A. Neronov^{ca}, K. Nomoto^{ax}, T. Nonaka^{ak},
 43 T. Ogawa^{az}, S. Ogio^{ar}, H. Ohmori^{az}, A.V. Olinto^{cd}, P. Orleañski^{bl},
 44 G. Osteria^w, A. Pagliaro^{y,u}, W. Painter^o, M.I. Panasyuk^{bp}, B. Panico^w,
 45 E. Parizot^l, I.H. Park^{bc}, B. Pastircak^{br}, T. Patzak^l, T. Paul^{ch},
 46 I. Pérez-Grande^{bw}, F. Peretto^{w,x}, T. Peter^{cb}, P. Picozza^{z,aa,az}, S. Pindado^{bw},
 47 L.W. Piotrowski^{az}, S. Piraino^q, L. Placidi^{ae}, Z. Plebaniak^{bk}, S. Pliego^{bd},
 48 A. Pollini^{bz}, Z. Polonsky^{ce}, E.M. Popescu^{bm}, P. Prat^l, G. Prévôt^l, H. Prieto^{bv},
 49 G. Puehlofer^q, M. Putis^{br}, J. Rabanal^j, A.A. Radu^{bm}, M. Reyes^{bx},
 50 M. Rezagadeh^{cd}, M. Ricci^v, M.D. Rodríguez Frías^{bv}, F. Ronga^v, G. Roudil^m,
 51 I. Rusinovⁱ, M. Rybczyński^{bj}, M.D. Sabau^{bu}, G. Sáez Cano^{bv}, H. Sagawa^{ak},
 52 Z. Sahnoun^b, A. Saito^{am}, N. Sakaki^{ak}, H. Salazar^{bf}, J.C. Sanchez Balanzar^{bd},
 53 J.L. Sánchez^{bt}, A. Santangelo^q, A. Sanz-Andrés^{bw}, M. Sanz Palomino^{bu},
 54 O. Saprykin^{bq}, F. Sarazin^{ce}, M. Sato^{au}, T. Schanz^q, H. Schieler^o, V. Scotti^{w,x},
 55 S. Selmane^l, D. Semikoz^l, M. Serra^{bx}, S. Sharakin^{bp}, H.M. Shimizu^{ap},
 56 K. Shinozaki^{ab,ac,l}, T. Shirahama^{at}, B. Spataro^v, I. Stan^{bm}, T. Sugiyama^{ap},
 57 D. Supanitsky^{bd}, M. Suzuki^{as}, B. Szabelska^{bk}, J. Szabelski^{bk}, N. Tajima^{az},
 58 T. Tajima^{az}, Y. Takahashi^{au}, H. Takami^{ay}, M. Takeda^{ak}, Y. Takizawa^{az},
 59 M.C. Talai^c, C. Tenzer^q, S.B. Thomas^{ck}, O. Tibolla^{bi}, L. Tkachev^{bn},
 60 H. Tokuno^{av}, T. Tomida^{an}, N. Tone^{az}, S. Toscano^{ca}, M. Traïche^a, R. Tsenovⁱ,
 61 Y. Tsunesada^{ar}, K. Tsuno^{az}, J. Tubbs^{cf}, S. Turriziani^{az}, Y. Uchihori^{ah},
 62 O. Vaduvescu^{bx}, J.F. Valdés-Galicia^{bd}, P. Vallania^{ab,ad}, G. Vankovaⁱ,
 63 C. Vigorito^{ab,ac}, L. Villaseñor^{be}, B. Vlcek^{bv}, P. von Ballmoos^m, M. Vrabel^{bs},
 64 S. Wada^{az}, J. Watanabe^{ao}, J. Watts Jr.^{cf}, M. Weber^o, R. Weigand Muñoz^{bt},
 65 A. Weindl^o, L. Wiencke^{ce}, M. Willeⁿ, J. Wilmsⁿ, Z. Włodarczyk^{bj},
 66 T. Yamamoto^{al}, J. Yang^{bb}, H. Yano^{as}, I.V. Yashin^{bp}, D. Yonetoku^{aj},
 67 S. Yoshida^{ag}, R. Young^{ci}, I.S. Zgura^{bm}, M.Yu. Zotov^{bp}, A. Zuccaro Marchi^{az}

68 ^aCentre for Development of Advanced Technologies (CDTA), Algiers, Algeria

69 ^bDepartment of Astronomy, Center of Research in Astronomy, Astrophysics, and
 Geophysics (CRAAG), Algiers, Algeria

70 ^cLPR at Department of Physics, Faculty of Sciences, University Badji Mokhtar, Annaba,
 71 Algeria

72 ^dLaboratory of Mathematics and Sub-Atomic Physics (LPMPs), University Constantine I,
 73 Constantine, Algeria

74 ^eLaboratory of Theoretical Physics LPT, University of Jijel, Jijel, Algeria

75 ^fDepartment of Physics, Faculty of Sciences, University of M'sila, M'sila, Algeria

76 ^gResearch Unit on Optics and Photonics, UROP-CDTA, Sétif, Algeria

77 ^hTelecom Laboratory, Faculty of Technology, University Abou Bekr Belkaid, Tlemcen,
 78 Algeria

79 ⁱSt. Kliment Ohridski University of Sofia, Bulgaria

80 ^jLAL, Université Paris-Sud, CNRS/IN2P3, Orsay, France

81 ^kOmega, Ecole Polytechnique, CNRS/IN2P3, Palaiseau, France

82 ^lAPC, Université Paris Diderot, CNRS/IN2P3, CEA/Irfu, Observatoire de Paris,
 83 Sorbonne Paris Cité, Paris, France

84 ^mIRAP, Université de Toulouse, CNRS, Toulouse, France

85 ⁿECAP, University of Erlangen-Nuremberg, Erlangen, Germany

87 ^oKarlsruhe Institute of Technology (KIT), Karlsruhe, Germany
88 ^pExperimental Physics Institute, Kepler Center, University of Tübingen, Tübingen,
89 Germany
90 ^qInstitute for Astronomy and Astrophysics, Kepler Center, University of Tübingen,
91 Tübingen, Germany
92 ^rIstituto Nazionale di Fisica Nucleare – Sezione di Bari, Bari, Italy
93 ^sUniversità degli Studi di Bari Aldo Moro, Bari, Italy
94 ^tDipartimento di Fisica e Astronomia – Università di Catania, Catania, Italy
95 ^uIstituto Nazionale di Fisica Nucleare – Sezione di Catania, Catania, Italy
96 ^vIstituto Nazionale di Fisica Nucleare – Laboratori Nazionali di Frascati, Frascati, Italy
97 ^wIstituto Nazionale di Fisica Nucleare – Sezione di Napoli, Naples, Italy
98 ^xDipartimento di Scienze Fisiche, Università di Napoli Federico II, Naples, Italy
99 ^yINAF – Istituto di Astrofisica Spaziale e Fisica Cosmica di Palermo, Palermo, Italy
100 ^zIstituto Nazionale di Fisica Nucleare – Sezione di Roma Tor Vergata, Rome, Italy
101 ^{aa}Dipartimento di Fisica, Università di Roma Tor Vergata, Rome, Italy
102 ^{ab}Istituto Nazionale di Fisica Nucleare – Sezione di Torino, Turin, Italy
103 ^{ac}Dipartimento di Fisica, Università di Torino, Turin, Italy
104 ^{ad}Osservatorio Astrofisico di Torino, Istituto Nazionale di Astrofisica, Pino Torinese, Italy
105 ^{ae}Uninettuno University, Rome, Italy
106 ^{af}DIETI, Università degli Studi di Napoli Federico II, Naples, Italy
107 ^{ag}Chiba University, Chiba, Japan
108 ^{ah}National Institute of Radiological Sciences, Chiba, Japan
109 ^{ai}Kindai University, Higashi-Osaka, Japan
110 ^{aj}Kanazawa University, Kanazawa, Japan
111 ^{ak}Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Japan
112 ^{al}Konan University, Kobe, Japan
113 ^{am}Kyoto University, Kyoto, Japan
114 ^{an}Shinshu University, Nagano, Japan
115 ^{ao}National Astronomical Observatory, Mitaka, Japan
116 ^{ap}Nagoya University, Nagoya, Japan
117 ^{aq}Institute for Space-Earth Environmental Research, Nagoya University, Nagoya, Japan
118 ^{ar}Graduate School of Science, Osaka City University, Japan
119 ^{as}Institute of Space and Astronautical Science/JAXA, Sagamihara, Japan
120 ^{at}Saitama University, Saitama, Japan
121 ^{aw}Hokkaido University, Sapporo, Japan
122 ^{av}Interactive Research Center of Science, Tokyo Institute of Technology, Tokyo, Japan
123 ^{aw}Nihon University Chiyoda, Tokyo, Japan
124 ^{ax}University of Tokyo, Tokyo, Japan
125 ^{ay}High Energy Accelerator Research Organization (KEK), Tsukuba, Japan
126 ^{az}RIKEN, Wako, Japan
127 ^{ba}Korea Astronomy and Space Science Institute (KASI), Daejeon, Republic of Korea
128 ^{bb}Ewha Womans University, Seoul, Republic of Korea
129 ^{bc}Sungkyunkwan University, Seoul, Republic of Korea
130 ^{bd}Universidad Nacional Autónoma de México (UNAM), Mexico City, Mexico
131 ^{be}Universidad Michoacana de San Nicolas de Hidalgo (UMSNH), Morelia, Mexico
132 ^{bf}Benemérita Universidad Autónoma de Puebla (BUAP), Puebla, Mexico
133 ^{bg}Centro de Desarrollo Aeroespacial – Instituto Politécnico Nacional (CDA-IPN), Mexico
134 City, Mexico
135 ^{bh}Universidad Autónoma de Chiapas (UNACH), Chiapas, Mexico
136 ^{bi}Centro Mesoamericano de Física Teórica (MCTP), Chiapas, Mexico
137 ^{bj}Jan Kochanowski University, Institute of Physics, Kielce, Poland
138 ^{bk}National Centre for Nuclear Research, Lodz, Poland
139 ^{bl}Space Research Centre of the Polish Academy of Sciences (CBK), Warsaw, Poland
140 ^{bm}Institute of Space Science ISS, Magurele, Romania
141 ^{bn}Joint Institute for Nuclear Research, Dubna, Russia
142 ^{bo}Central Research Institute of Machine Building, TsNIMMash, Korolev, Russia

143 ^{bp}Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow,
 144 Russia
 145 ^{bq}Space Regatta Consortium, Korolev, Russia
 146 ^{br}Institute of Experimental Physics, Kosice, Slovakia
 147 ^{bs}Technical University Kosice (TUKE), Kosice, Slovakia
 148 ^{bt}Universidad de León (ULE), León, Spain
 149 ^{bu}Instituto Nacional de Técnica Aeroespacial (INTA), Madrid, Spain
 150 ^{bv}Universidad de Alcalá (UAH), Madrid, Spain
 151 ^{bw}Universidad Politécnica de Madrid (UPM), Madrid, Spain
 152 ^{bx}Instituto de Astrofísica de Canarias (IAC), Tenerife, Spain
 153 ^{by}KTH Royal Institute of Technology, Stockholm, Sweden
 154 ^{bz}Swiss Center for Electronics and Microtechnology (CSEM), Neuchâtel, Switzerland
 155 ^{ca}ISDC Data Centre for Astrophysics, Versoix, Switzerland
 156 ^{cb}Institute for Atmospheric and Climate Science, ETH Zürich, Zurich, Switzerland
 157 ^{cc}Space Science Laboratory, University of California, Berkeley, USA
 158 ^{cd}University of Chicago, Chicago, USA
 159 ^{ce}Colorado School of Mines, Golden, USA
 160 ^{cf}University of Alabama in Huntsville, Huntsville, USA
 161 ^{cg}NASA Jet Propulsion Laboratory, Pasadena, USA
 162 ^{ch}Lehman College, City University of New York (CUNY), New York, USA
 163 ^{ci}NASA – Marshall Space Flight Center, Huntsville, USA
 164 ^{cj}Vanderbilt University, Nashville, USA
 165 ^{ck}University of Utah, Salt Lake City, USA

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 $2.3 \text{ }\mu\text{s}$ 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
 ~ 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 $\sim 780 \text{ km}^2$ 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.

167 *Keywords:* EUSO-Balloon, JEM-EUSO, ultra-high energy cosmic ray,

168 extensive air shower, airglow

169 *PACS:* 95.55.Vj 95.85.Ry, 96.50.sd, 92.60.hw,

170 **1. Introduction**

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

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

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

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

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

213 In 2016, the TUS instrument was launched to start space-based UHECR
214 observations in an orbit at $\sim 500 \text{ km}$ above sea level (asl.) [20]. Using a $\sim 2 \text{ m}^2$

215 reflective Fresnel telescope with 256 PMTs, it covers a $\sim 9^\circ$ FoV corresponding to
216 an order of $S_{\text{obs}} \sim 6000 \text{ km}^2$ area. Simulation studies show that this instrument
217 is capable of detecting EASs from UHECRs with 10^{20} eV energies.

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

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

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

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

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

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

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

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

275 it is only important to quantify the affected fraction of the instantaneous
276 observation area rather than the light intensity.

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

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

292 *2.2. Former balloon-borne measurements*

293 As part of the drive for space-based UHECR observations, there have been
294 several balloon-borne experiments aiming at investigating background light [34,
295 35, 36, 37]. A major goal of these experiments was to determine the absolute
296 intensity, I_0 , of the diffuse light under clear atmosphere conditions in moonless
297 night. Results have been presented by two groups.

298 The Background Bypass (BaBy) balloon experiment [34] was first carried
299 out over the land and sea off Sicily, Italy, at ~ 26 km asl. on July 30, 1998. The
300 instrument was purely designed for diffuse light measurements that consisted
301 of two sets of collimators and PMTs mounted with UV band-pass filters. The
302 estimated I_0 value over the sea without ambient light of the populated areas
303 was $\sim 400\text{--}450$ photons m^{-2} sr^{-1} ns^{-1} in the $300\text{--}500$ nm band. The other
304 flight of BaBy reaching ~ 39 km asl. took place over the Mediterranean Sea on

305 July 11, 2002 [35]. The average I_0 value was $310 \text{ photons m}^{-2} \text{ sr}^{-1} \text{ ns}^{-1}$ in
306 the 300–400 nm band. Another flight attempt in 2001 was reported with more
307 than twice the intensity in comparison with the above value. We consider that
308 it was due to the low flight altitude of $\sim 15\text{--}30$ km and possible light pollution
309 by the artificial light.

310 The NIGHTGLOW balloon experiment took place over Texas, USA, at
311 ~ 30 km asl. on July 5, 2000 [36]. The instrument was composed of elements
312 used for real fluorescence telescopes; a ~ 36 cm diameter spare mirror and UV
313 band-pass filters from the High Resolution Fly’s Eye (HiRes) experiment [38]
314 and two PMTs from the Fly’s Eye experiment [39]. These filters were selected
315 for the maximum SNR for EAS detections. The I_0 value in the nadir direction
316 was found to be $300 \pm 41 \text{ photons m}^{-2} \text{ sr}^{-1} \text{ ns}^{-1}$ in the 300–400 nm band.
317 By pointing the instrument to the zenith, the total intensity of the downward
318 component was estimated to be $691 \pm 34 \text{ photons m}^{-2} \text{ sr}^{-1} \text{ ns}^{-1}$.

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

325 **3. EUSO-Balloon**

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

330 *3.1. The EUSO-Balloon telescope*

331 The EUSO-Balloon telescope is the main instrument of the balloon payload
332 with a total mass of 467 kg. It is installed with crash rings, designed to protect

333 the instrument in the case of landing on dry land as well as a floater to keep
334 the electronics subsystems dry in the case of a possible water landing [42, 43].

335 EUSO-Balloon is capable of imaging in the UV band. This is a
336 major difference when compared to the former experiments. The telescope
337 consists of two Fresnel lenses made of 8 mm thick PMMA, UV transmitting
338 polymethylmethacrylate [44, 45]. Based on the technologies developed for
339 JEM-EUSO [46], the lenses were fabricated as 1.2 m diameter circular lenses
340 and then were cut to form a square of side 1 m with round corners. The nominal
341 entrance aperture, S_{opt} , is 0.96 m². To avoid any damage during landing, the
342 optics is recessed inside the overhanging walls. These walls are extended beyond
343 the front lens to act as a baffle, blocking photons from large off-axis angles.

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

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

357 The sensitivity of the instrument is determined by the detection efficiency
358 of the MAPMTs, the transmittance of the BG3 filters and the response of the
359 optical system. The overall efficiency is highest in the ~330–400 nm band
360 where dominant lines of fluorescence light lie to give a more precise energy
361 estimation of the incident UHECRs. The sensitive range extends between ~250
362 and ~500 nm. The lower limit is due to the transmittance of PMMA lenses,
363 while the upper limit is given by that of BG3 filters and the quantum efficiency

364 of the MAPMTs. It is worth mentioning that the sensitivity above ~ 400 nm
365 allows the collection of more of the Cherenkov light produced in the EASs. This
366 light is in general not desirable for ground-based fluorescence telescopes since
367 it introduces uncertainties in the analysis of detected EAS events [51]. Seen
368 from above, such light is back-scattered from the Earth's surface or clouds and
369 allows for a more precise determination of the arrival direction of UHECRs by
370 constraining the geometry of EAS events [17, 52].

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

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

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

395 *3.2. The EUSO-Balloon flight*

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

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

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

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

420 Figure 1 displays the GPS ground track of the EUSO-Balloon optical axis
421 by the solid curve. The bold curve denotes the track during the ToI. The
422 launch and landing positions are marked in addition to the hourly positions.
423 The dashed lines enclose the Region of Interest (RoI) for this work. The
424 color scale represents the Visible band Digital Number (VDN) from the 2013
425 DMSP (Defense Meteorological Satellite Program) satellite data [57].

426 VDN scales to the fluxes in the $0.35\text{--}2\ \mu\text{m}$ band by 64 integer levels. We
427 make use of the annual average data in cloud-free conditions given every $30''$ grid
428 in geographic coordinates, i.e., at a resolution of ~ 610 m on the east-west and
429 ~ 930 m on the north-south directions. The VDN is 0 in most of the RoI, while
430 the rest is registered with a VDN of 4 or higher.

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

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

441 At the beginning of the ToI, the EUSO-Balloon telescope reached
442 36.4 km asl. Until 03:30, it continued ascending to the float altitude of about
443 38.2 km which was maintained within a $\sim \pm 0.2$ km oscillation with a ~ 5 min
444 period. At this altitude, the atmospheric pressure is ~ 4 hPa. To avoid coronal
445 discharge at such a low pressure that could lead to a breakdown of the entire
446 mission, we limited the high voltage applied on the MAPMTs to -950 V against
447 the nominal operational voltage of -1100 V.

448 The EUSO-Balloon telescope was freely rotating around the optical axis.
449 To describe such a rotation, we define the orientation, Φ_0 , of the telescope by
450 the eastward angle, measured from the true north to the x -axis of the PDM.
451 Hereafter, azimuth with respect to the horizontal coordinates is defined in the
452 same way.

453 Figure 3 displays the orientation Φ_0 of the EUSO-Balloon telescope as a
454 function of the time t . North, east, south and west directions correspond to
455 $0^\circ, +90^\circ, \pm 180^\circ$ and -90° , respectively. The ToI is indicated by the arrow.

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

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

462 The pointing direction of the optical axis of the telescope also varied with
463 a similar trend. The maximum off-axis angle from the nadir is estimated to be
464 $\sim 1.8^\circ$ [58]. Such variation of the attitude is taken into account in the ground
465 track shown on Fig. 1 which is used as a reference for location during the
466 analysis.

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

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

478 3.3. The elementary data

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

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

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

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

488 where the pixel number is hereafter referenced by the subscript i . The $\langle n \rangle$ value
489 represents the average for the interval of 320 μs ($= 128 \times 2.5 \mu\text{s}$) with the total
490 gate time of 294 μs ($= 128 \times 2.3 \mu\text{s}$). The time resolution is $\sim 52 \text{ ms}$ ($\approx 1/19 \text{ [Hz]}$)
491 given by trigger rates. This value in most cases represents the average noise level
492 due to diffuse light.

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

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

505 4. Analysis

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

511 4.1. Count rate determination

512 In this work, we use the average count rate $\langle n \rangle$ over a packet from Eq. (1).
513 The readout count n shows non-linearity with respect to the number, n_{pe} , of

514 photoelectrons (pe) collected on the first dynode. This relation is expressed by
 515 the following theoretical formula [62]:

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

516 where $\tau_0 \sim 30$ ns corresponds to the double pulse resolution in photon counting
 517 by the readout electronics and was experimentally determined [63]. Substituting
 518 the $\langle n \rangle$ value given by Eq. (1) for the n value in this equation, we can solve for
 519 the n_{pe} value. The solution is double-valued in most cases. We choose the lower
 520 value of the solutions and call the ‘count rate’, N , in units of pe pixel⁻¹ GTU⁻¹.

521 For $n=1$ and 10 counts pixel⁻¹ GTU⁻¹, the corresponding N values
 522 are 1.01 and 11.7 pe pixel⁻¹ GTU⁻¹, respectively. In the case of $n \gtrsim$
 523 28 counts pixel⁻¹ GTU⁻¹, no solution exists. Thus we force $\langle n \rangle$ values to have
 524 an upper limit of ~ 28 . This gives the bound of $N < 68$ pe pixel⁻¹ GTU⁻¹. The
 525 fraction of such cases is $\sim 10^{-5}$ of the whole $\langle n \rangle$ data set.

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

535 For the detection efficiency, ε_{det} , the product of the photocathode’s quantum
 536 efficiency and the collection efficiency of the MAPMT, and transmittance, T_{BG3} ,
 537 of the BG3 filters, the wavelength dependence of the ε efficiency is given as
 538 follows:

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

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

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

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

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

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

$$\hat{N}_i = \frac{\langle\varepsilon(378 \text{ [nm]})\rangle}{\varepsilon_i(378 \text{ [nm]})} \cdot N_i. \quad (5)$$

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

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

559 where the packet number is hereafter indicated by the subscript m . On average,
560 $\sim 90\%$ of the selected pixels were active during the ToI.

561 4.2. The optics response model to incident directions

562 The EUSO-Balloon optics is optimized for the UV photons emitted from
563 EASs, essentially a dynamic confined spot of light with a small apparent lateral
564 spread focused on a limited area on the PDM. In general, the displacement, d ,
565 of the focal spot from the center of the PDM increases with the incident off-axis

566 angle, ϑ , from the optical axis. In this work, we evaluate the relation of these two
 567 values by using simulations of the optical system. Applying the EUSO-Balloon
 568 configuration [65], we make use of the GEANT4 module [66, 67] implemented
 569 in the Offline framework [68].

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

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

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

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

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

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

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

	$\langle \partial d / \partial \vartheta \rangle$ [mm per 1°]		
	$\lambda=330$ nm	$\lambda=365$ nm	$\lambda=400$ nm
$\varphi' = \pm 0^\circ$	14.20 ± 0.08	15.01 ± 0.03	14.73 ± 0.03
$\varphi' = \pm 15^\circ$	14.29 ± 0.08	15.00 ± 0.03	14.70 ± 0.02
$\varphi' = \pm 30^\circ$	14.29 ± 0.07	15.00 ± 0.02	14.72 ± 0.02
$\varphi' = \pm 45^\circ$	14.33 ± 0.05	15.15 ± 0.02	14.80 ± 0.01

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

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

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

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

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

607 According to Eqs. (7) and (8), we assign a nominal direction seen by each
 608 pixel at its center position (x, y) represented by ϑ and φ angles as follows:

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

609 As seen in Fig. 5, the PSF may extend beyond the size of a pixel. A certain
 610 fraction of the photons on the pixel are not from the nominal FoV of that pixel.
 611 The inverse function of Eq. (9) can thus only deduce a likely incident direction
 612 of each photon reaching the PDM.

613 The reciprocal of the derivative $\langle \partial d / \partial \vartheta \rangle$ is equivalent to ‘plate
614 scale.’ The nominal angle of view, α_{pix} , seen by each pixel is
615 $\approx 0.20^\circ (= 2.88 \text{ [mm]} / 14.6 \text{ [mm per } 1^\circ])$. Along the PDM axis, considering
616 ± 3 MAPMTs yields an equivalent dimension of $\pm 82.5 \text{ mm} (= \pm 3 \times 27.5 \text{ mm})$ as
617 seen in Fig. 4. By doubling the ϑ value in Eq. (7) to match $d = 82.5 \text{ mm}$, the
618 nominal angle of view, α_{PDM} , of the PDM is defined as follows:

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

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

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

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

622 To describe the incident direction of photons, we define a polar coordinate
623 system by the nadir angle, Θ , and the azimuth, Φ , at the EUSO-Balloon
624 telescope. We assume that the position of the telescope is above the GPS
625 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:

$$\vartheta \equiv \Theta \quad (12a)$$

$$\varphi \equiv \Phi - \Phi_0(t), \quad (12b)$$

626 by taking into account the orientation Φ_0 of the telescope as shown in Fig. 3.

627 Figure 6 illustrates the key geometry used in the analysis. Definitions of key
628 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{GE} can be expressed using the cosine theorem as follows:

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

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

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

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

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

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:

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

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

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

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

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

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

$$\langle \tilde{N} \rangle_k = \frac{\sum_m \sum_i [\delta_{i,k}(t_m) \cdot \hat{N}_i(t_m)]}{\sum_m \sum_i \delta_{i,k}(t_m)}. \quad (17)$$

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

647 5. Results

648 5.1. The time evolution of the normalized count rates

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

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

662 In the time interval between 04:38 and 04:52, referred to as Case (a), when
 663 the $\langle \hat{N} \rangle$ values are low and stable, the average $\langle N \rangle$ values are evaluated by
 664 several times 10^4 independent samples from the active pixels. In typical packets
 665 in Case (a), all or almost of all 650 selected pixels were active and the statistical
 666 error is irrelevant. The relative SD, $\hat{\sigma}/\langle \hat{N} \rangle$, among these pixels is on the order of

667 $\sim 15\%$. This deviation includes the non-uniform response of the optics to diffuse
668 light and possible non-uniform light distribution in the FoV.

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

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

686 5.2. The normalized count rates projected onto geographic coordinates

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

690 The uncertainties in $\langle \tilde{N} \rangle$ value are correlated with that of location. Bad
691 assignment of the nominal direction seen by each pixel introduces an artificial
692 fluctuation into Eq. (17). In the following, the maximum uncertainty in location,
693 in terms of misplacement from the position given by Eqs. (15a) and (15b), is
694 estimated for the float altitude $H_0 = 38$ km. Unless otherwise mentioned, they
695 are intended to represent the positions seen at the corners of the nominal FoV.

696 The statistical error of the $\langle \tilde{N} \rangle$ values primarily depends on the number,

697 $\sum_m \sum_i \delta_i(t_m)$, of measured packets per grid point. It can be up to 130 packets
698 with an average of ~ 12 . In general, the grid points near the boundary area have
699 a few packets used.

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

705 At the typical ground speed $\langle v_0 \rangle$, EUSO-Balloon traversed the L_{PDM} length
706 corresponding to the nominal angle of view α_{PDM} for a duration of around
707 15 min ($\sim L_{\text{PDM}}/\langle v_0 \rangle$). The motion and rotation of the EUSO-Balloon telescope
708 could lead to a difference in time between the first and last measured packets
709 of up to ~ 40 min. The local time of the ToI was 23:08–01:48. Particularly in
710 the populated zone, variability due to human activities cannot be ruled out.

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

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

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

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

727 from what was designed by up to ~ 1 mm in the form of gaps between neighboring
 728 BG3 filters. Such a misplacement could introduce an error in the assigned
 729 direction by the order of $\sim 0.07^\circ$ ($= 1 \text{ [mm]} / 14.6 \text{ [mm per } 1^\circ]$) resulting in a
 730 ~ 50 m uncertainty in the projected position in the whole observation area.

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

737 During the ToI, the orientation of the EUSO-Balloon telescope was
 738 monitored every 1 s. Thus the maximum uncertainty, $\Delta\Phi_0$, of the orientation
 739 is $\sim 7^\circ$ from its maximum angular velocity. It was the case in the early part of
 740 the ToI and in the eastern part of the RoI. This leads to the maximum error,
 741 $(L_{\text{PDM}}/\sqrt{2}) \cdot \Delta\Phi_0$, in location to be ~ 650 m. This effect then decreases with
 742 the time as rotation and oscillation damped during the flight in the ToI.

743 **6. Discussion**

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

750 *6.1. Correlation between the normalized count rate distribution and* 751 *ground-based sources*

752 In Fig. 8, several hotspots and extended light sources in the Timmins area
 753 and structures in the Montcalm Mine area are clearly visible. In order to
 754 compare with a light source distribution mainly in the visible band, we use

755 the DMSP data shown in Fig. 1. To identify the counterparts to the hotspots,
756 we utilize public online map services [69, 70] and Landsat Imagery [71].

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

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

769 In order to find the correlation with the known light sources, we define the
770 hotspots as spatially confined zones with high $\langle \tilde{N} \rangle$ values. To avoid the selection
771 of hotspots that are purely due to fluctuations, a cut of 120 pe GTU^{-1} is set on
772 the sum of the $\langle \tilde{N} \rangle$ values of 24 ($= 6 \times 4$) grid points, i.e., an average value of
773 $\langle \tilde{N} \rangle > 5 \text{ pe pixel}^{-1} \text{ GTU}^{-1}$. The grid separation in this discussion corresponds
774 to a $\sim 220 \text{ m}$ on both coordinates.

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

779 For each hotspot, the maximum $\langle \tilde{N} \rangle$ grid point is likely to be correlated
780 with its counterpart source. Hotspot (X1) is found in the area without a local
781 VDN maximum. It coincides with the position of a mining ground at Pamour.
782 In UHECR observations, good accuracy in location is an essential requirement
783 for the analysis of EAS events. The capability of finding temporary intense
784 sources or ones not shown on the map also helps eliminate the fraction of the
785 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.

Label	Nearest time	Maximum $\langle \tilde{N} \rangle$ grid point			Stretch	Counterparts to maximum $\langle \tilde{N} \rangle$ grid point (Remarks for the whole hotspot)
		Lat.	long.	$\langle \tilde{N} \rangle$		
(H1)	03:08	48°32'57"N	81°03'19"W	12	0.1	Industrial facility (boundary)
(H2)	03:08	48°32'54"N	81°04'22"W	23	1.4	Industrial complex with railroad yard, power plant etc.
(H3)	03:08	48°32'57"N	81°06'30"W	25	2.3	Mine pit (resolved into two pits ~ 1 km apart)
(H4)	03:08	48°33'57"N	81°06'42"W	29	1.2	Mine pond
(X1)	03:09	48°30'55"N	81°06'48"W	11	0.2	Mine pit (no corresponding VDN maximum)
(B1)	03:16	48°33'10"N	81°10'47"W	62	2.2	Mining ground
(P1)	03:22	48°28'58"N	81°12'19"W	21	8.5	South Porcupine community (also resolved to Pottsville and Porcupine at ~ 2 – 3 km to the east)
(P2)	03:30	48°28'13"N	81°14'02"W	31	0.5	Mining ground (boundary)
(P3)	03:31	48°27'59"N	81°14'52"W	23	0.2	Mine pit (boundary)
(T1)	03:34	48°29'39"N	81°16'54"W	6.3	0.3	Mining ground
(T2)	03:36	48°32'21"N	81°17'23"W	9.4	0.6	Cement factory
(T3)	03:37	48°28'33"N	81°19'15"W	29	27	Park on a residential zone boundary. Commercial facility and high $\langle \tilde{N} \rangle$ zones
(T4)	03:42	48°29'34"N	81°21'28"W	20	0.5	Industrial plant on the bank of Mattagami River
(A1)	03:46	48°33'55"N	81°22'13"W	16	0.1	Airport parking lot (boundary)
(M1)	05:30	48°40'00"N	82°05'45"W	11	0.4	Mining ground
(M2)	05:30	48°40'26"N	82°05'56"W	11	0.1	Facility ~ 0.9 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 $\text{pe pixel}^{-1} \text{GTU}^{-1}$. The stretch of the confined hotspot area is indicated in units of km^2 .

Hotspots (H1), (P2), (P3) and (A1) are measured near the boundary of the nominal FoV with a limited number of packets.

786 In the following, we discuss some of the characteristic hotspots and their
787 counterparts. Additionally, lower $\langle \tilde{N} \rangle$ values are found in some areas which
788 contain potential light sources. Possible interpretations for such cases are also
789 given.

790 In Example (i) of Fig. 4, Hotspot (H1) is recognized in the bottom-right
791 MAPMT. Hotspot (X1) is in the upper part of the PDM. In the same example,
792 Hotspots (H2) and (H3) are clearly identified. Hotspot (H4) is on the bottom
793 edge.

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

801 Before $\sim 04:00$, several hotspots contribute to the large variations of
802 the $\langle \hat{N} \rangle$ value seen in Fig. 7. Distinctly high values are found around
803 03:14–03:16. Apart from this, contributions from the individual hotspots are
804 not distinguished early in the ToI. This behavior can be explained by the passage
805 of Hotspot (B1) in the nominal FoV for a short interval. This hotspot contains
806 the data with saturated count rates. Thus the $\langle \tilde{N} \rangle$ values shown in Table 2
807 represent the lower limits.

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

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

818 In contrast, relatively low $\langle \tilde{N} \rangle$ values are observed over the populated zone
819 around the VDN maximum of Area (T). A possible interpretation is an unstable
820 behavior of the PDM that decreases the number of active pixels. Such situations
821 tended to occur where a large number of photoelectrons were generated in a
822 broad part of the PDM. As for the impact of this effect on UHECR observations,
823 detections of EASs are primarily suppressed in such an area with too intense
824 light and only determination of the affected area is relevant. In the upgraded

825 electronics, such a problem has been overcome and a dynamic range of photon
 826 counting has been extended to a few hundred photoelectrons [73].

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

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

839 At $\sim 05:44$, additional peaks are found in Fig. 7. At that time, the potential
 840 light sources in Area (M) were well out of the nominal FoV of the EUSO-Balloon
 841 telescope. An interpretation of these peaks is that the attitude of the instrument
 842 might be affected and instantaneously pointed to the direction of Hotspots (M1)
 843 and (M2). The GPS data show a significant impulsive acceleration, \ddot{H}_0 , of
 844 $> 2 \text{ m s}^{-2}$ in the vertical direction in comparison to its root mean square
 845 $\sqrt{\langle \ddot{H}_0^2 \rangle} \sim 0.5 \text{ m s}^{-2}$ over the ToI.

846 6.2. Implications for space-based UHECR observations

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

853 In the aforementioned work, it was assumed that the effect from the Moon is
 854 the main component of the temporal \bar{N} variation in the orbit. The impact from

855 the local light component, especially artificial light, was separately evaluated by
856 analyzing the distribution of visible light fluxes from the DMSP data. These
857 distributions were used to evaluate two parameters: the observational duty
858 cycle, η , and the fraction, f_{loc} , of the area with intense local light sources.

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

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

867 The results of the EUSO-Balloon mission allow for similar studies, but with
868 real data, i.e., the $\langle \hat{N} \rangle$ distribution from Eq. (6) and the $\langle \tilde{N} \rangle$ distribution from
869 Eq. (17). The data from this work cover a ~ 2.5 hour time interval and a
870 $\sim 780 \text{ km}^2$ area and thus the given distributions represent the particular case
871 of the EUSO-Balloon flight. This time and area are small compared with
872 those potentially achieved by space-based missions, i.e., several years of mission
873 lifetime and an order of 10^8 km^2 area on the Earth.

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

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

883 Although the trigger algorithms need to consider further effects such as
884 different pixel efficiencies [26], the average normalized count rates are used for a
885 first order discussion. In practice, the η value is determined by the permissible

886 limit, \bar{N}_{lim} , of the average count rate which allows the trigger algorithms to be
 887 operational and is expressed as follows:

$$\eta (< \bar{N}_{\text{lim}}) \equiv \frac{T_{\text{obs}}}{T_0} = \frac{1}{T_0} \cdot \int_0^{\bar{N}_{\text{lim}}} \frac{dT}{d\bar{N}} d\bar{N}. \quad (18)$$

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

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

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

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

907 in units of $\text{km}^2 \text{ sr}$. Here, the effects of clouds and the local light component
 908 have been omitted.

The \bar{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:

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

$$= \int_0^{\bar{N}_{\text{lim}}} \left[\dot{A}_0 \left(\sqrt{\frac{N_0}{\bar{N}}} \cdot E_0 \right) \cdot \left(\frac{dT}{d\bar{N}} \right) \right] d\bar{N}. \quad (20b)$$

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

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

$$A(\infty) \approx \dot{A}_0(\infty) \cdot \kappa_C \cdot \eta \cdot (1 - f_{\text{loc}}) \cdot T_0, \quad (21)$$

915 where κ_C is the cloud efficiency. This parameter describes the ratio of the
 916 aperture taking into account the presence of clouds to the one for clear
 917 atmosphere conditions [17, 22, 52].

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

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

931 *6.3. The absolute intensity of diffuse light*

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

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

938 As the reflectivity of the clouds is higher, the time interval and area with
939 lowest count rates are considered to represent a case with little influence from
940 clouds, i.e., clear atmosphere. Such conditions were present in Case (a) between
941 04:38 and 04:52 as mentioned in Sec. 5. At 04:36, 04:48 and 04:55, the pilot
942 reported clear sky conditions above the helicopter.

943 In addition, similar conditions were considered to be present between 05:30
944 and 05:48 referred to as Case (b). The pilot confirmed such conditions at 05:29,
945 05:35 and 05:46. EUSO-Balloon was flying through and away from Area (M) as
946 seen in Example (ii) of Fig. 4. $\langle \hat{N} \rangle$ values are as low as in Case (a) seen in Fig. 7
947 if the contributions associated with Hotspots (M1) and (M2) are eliminated by
948 strictly using 67 pixels in two MAPMTs out of the 650 selected pixels.

949 Figure 12 displays the $\langle \hat{N} \rangle$ distributions for Cases (a) and (b) shown as the
950 solid and dashed histograms, respectively. Each histogram is normalized to the
951 total number of packets in use: 2.3×10^4 for Case (a) and 1.5×10^4 for Case (b).

952 For the reference \hat{N}_0 value, we quote the mode of the distribution for Case (a)
953 obtained as follows:

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

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

957 *6.3.2. The optics response to diffuse light*

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

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

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

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

$$\Omega_{\text{sim}} = \int_{\Omega} \cos \vartheta d\Omega = \int_0^{2\pi} \int_0^{\vartheta_{\text{lim}}} (\cos \vartheta \cdot \sin \vartheta) d\vartheta d\varphi. \quad (24)$$

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

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

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

978 Figure 13 displays the average pixel acceptance $\langle \tilde{a} \rangle$ over the selected
 979 650 pixels to diffuse light as a function of the wavelength. The shaded
 980 interval indicates the SD component, $(\bar{\sigma}/\langle \bar{\beta} \rangle) \cdot \langle \tilde{a} \rangle$, over these pixels due to the
 981 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 \tilde{a} for the diffuse light models.

Model	Relative abundance $\frac{dI_0}{I_0}$ in wavelength λ [nm] band					Spectrum-weighted pixel acceptance \tilde{a} [m ² sr]
	300–340	340–380	380–420	420–460	460–500	
Airglow	37%	39%	18%	5%	1%	0.95×10^{-6}
Starlight	15%	27%	24%	20%	15%	0.88×10^{-6}
Light bulb	0%	1%	12%	31%	57%	0.44×10^{-6}

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

985 6.3.3. An interpretation for the absolute intensity estimation

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

$$I_0 = \int_{\lambda} \frac{dI_0}{d\lambda} d\lambda. \quad (26)$$

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

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

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

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

996 Table 3 summarizes the relative abundances, dI_0/I_0 , in different λ bands for
 997 the airglow, starlight and light bulb models together with the corresponding
 998 \tilde{a} value in Eq. (27). A value of unity corresponds to the intensity in the
 999 300–500 nm band, according to Eq. (26).

1000 The airglow model is deduced from the data taken by the Ultraviolet Visual
 1001 Echelle Spectrograph (UVES) [74, 75]. The starlight model is quoted from
 1002 Ref. [33]. The light bulb model is from Ref. [80], intended for a lower bound of
 1003 the \check{a} value.

1004 For the natural light source models, photons are first sampled according
 1005 to these models. Using the Monte Carlo method by the ‘libRatran’ code [76,
 1006 77], these photons are then traced from the top of the atmosphere and the
 1007 back-scattering in the atmosphere is simulated to obtain their spectra on the
 1008 telescope at 38 km asl.

1009 The airglow emission has a continuum spectrum characterized by prominent
 1010 lines in the 300–400 nm band. Its back-scattered light also shows a dominant
 1011 abundance for short λ . The back-scattered starlight has a continuum spectrum
 1012 with its differential intensity rising with increasing λ . Another potential natural
 1013 light source is zodiacal light which has a similar spectrum to the starlight model.
 1014 Its contribution is considered to be very little at the local solar time of ~ 0 h in
 1015 the ToI.

1016 Under clear atmosphere conditions, Rayleigh scattering by molecules is the
 1017 dominant process of radiation transfer [78]. For the light of extraterrestrial
 1018 origin, relative abundances below ~ 320 nm are largely suppressed due to
 1019 absorption by ozone molecules [79]. The response of the optics also renders
 1020 contributions below ~ 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:

$$N = \check{a} \cdot I \quad (28a)$$

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

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

Table 4: I_0 values deduced for different spectrum models.

	300–500 nm	300–400 nm
Model (this work)	Consistent I_0 [photon m ⁻² sr ⁻¹ ns ⁻¹]	
Airglow	~320	~260
Starlight	~300	~170
Light bulb	~640	~30

1024 Table 4 summarizes consistent I_0 values in the 300–500 nm and
 1025 300–400 nm bands deduced for different spectrum models. According to
 1026 abundances below 400 nm in Table 3, the intensities in the 300–400 nm band
 1027 were estimated. They may be compared with former experiments [34, 35, 36].

1028 In Case (a), the diffuse light seen by the EUSO-Balloon telescope is mostly
 1029 from airglow and starlight components with an unknown mixture. Artificial light
 1030 is highly unlikely to dominate the measured count rate in the forest. Thus, the
 1031 values listed for artificial light would give conservative constraints. Note that
 1032 airglow is a dynamic phenomenon. Its intensity varies in time and geographic
 1033 position as well as by the influence of geomagnetic activity and atmospheric
 1034 tides [81]. These variations could even exceed these model dependences.

1035 A possible lower limit may be inferred with a virtual ideal instrument by
 1036 assuming that all the photons incident on the optics aperture would focus on
 1037 the nominal angle of view α_{pix} of a pixel. As the pixel efficiency $\langle \varepsilon \rangle$ is maximum
 1038 at ~ 378 nm, the maximum possible pixel acceptance for such an instrument is
 1039 given by $\langle \varepsilon(378 \text{ [nm]}) \rangle \cdot S_{\text{opt}} \cdot (\alpha_{\text{pix}})^2$ and is 2.2×10^{-6} m² sr. Applying it to
 1040 Eq. (28b) yields ~ 130 photons m⁻² sr⁻¹ ns⁻¹ to the reference count rate \hat{N}_0 in
 1041 Eq. (22).

1042 With the assumed optics response model, further uncertainty in the \check{a}
 1043 values may be derived from the response of the EUSO-Balloon instrument.
 1044 By taking into account the 7% uncertainty $\Delta\varepsilon/\varepsilon$ in pixel efficiencies from
 1045 the PDM calibration and the pixel acceptance dependence of $\sim 11\%$, the
 1046 overall uncertainty is $\sim 13\%$ $\left(= \sqrt{(\Delta\varepsilon/\varepsilon)^2 + (\bar{\sigma}/\langle \bar{\beta} \rangle)^2} \right)$. Although not all

1047 selected 650 pixels gave pre-flight calibration, the selection of pixels allows $\pm 11\%$
1048 level uncertainty of a possible variation of the pixel efficiency during the flight.
1049 As mentioned in Sec. 5, the relative SD in normalized count rates among pixels
1050 is $\sim 15\%$ during the Case (a) time interval and thus it is consistent with the
1051 hypothesis of illumination of uniform diffuse light within the uncertainty of
1052 $\sim 18\%$ ($= \sqrt{(13\%)^2 + (11\%)^2}$).

1053 *6.4. Outlook*

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

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

1072 Thanks to the trigger system, EUSO-SPB had the potential to detect a few
1073 EAS events if it had flown as long as a few months achieved in the former
1074 SPB flights. The observable energy range of the cosmic rays was lowered to
1075 a few times 10^{18} eV. The data analysis of EUSO-SPB, more oriented to EAS
1076 detections and estimation of the exposure to cosmic rays as discussed in Sec. 6.2

1077 is underway.

1078 Mini-EUSO is a 25 cm telescope with a refractive Fresnel optics mounted on
1079 the UV-transparent, nadir-facing window of the Russian module *Zvezda* on the
1080 ISS. With one PDM, it is designed to observe a 44° square FoV, corresponding
1081 to a square of side ~ 300 km on the Earth's surface. Orbiting above the
1082 airglow layer, Mini-EUSO is capable of measuring the sum of direct and indirect
1083 components of diffuse light. The ISS orbit that ranges within latitudes of $\pm 51.6^\circ$
1084 allows for the measurements at various positions over the Earth.

1085 It is expected to provide interesting data on UV-luminous phenomena in
1086 the upper atmosphere [86]. For example, it will be possible to achieve more
1087 detailed information on airglow emissions, in particular, variation over time and
1088 position on the Earth, as well as the response to solar and geomagnetic activities.
1089 Measurements with large observation area will provide an opportunity to
1090 investigate different scale phenomena in airglow science such as the effect of
1091 the atmospheric gravity wave [87].

1092 **7. Conclusions**

1093 The EUSO-Balloon mission was designed, constructed and flown operating
1094 a ~ 1 m² refractive Fresnel optics and a prototype PDM. Towards space-based
1095 UHECR observations, it was the first pathfinder mission in the JEM-EUSO
1096 program that took in-flight measurements in August 2014. After an 8 hour
1097 stratospheric flight, the instrument was safely recovered, allowing post-flight
1098 calibration in the laboratory.

1099 In this work, we analyze ~ 2.5 hours of the instrument data, in conjunction
1100 with the GPS data, post-flight PDM calibration and ray trace simulations. The
1101 main results obtained are the normalized count rates as a function of the time
1102 and their distribution on geographic coordinates over a ~ 780 km² area. The
1103 high count rates with rapid variations are shown to be due to the developed
1104 area where such excesses are caused by the local artificial light sources. The
1105 lowest count rates are found when flying over forested areas. In general, the

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

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

1124 **Acknowledgments**

1125 This work was partially supported by Basic Science Interdisciplinary
1126 Research Projects of RIKEN and JSPS KAKENHI Grant (22340063,
1127 23340081, and 24244042), by the Italian Ministry of Foreign Affairs
1128 and International Cooperation, by the Italian Space Agency through the
1129 ASI INFN agreement n. 2017-8-H.0, by NASA award 11-APRA-0058
1130 in the USA, by the French space agency CNES, by the Deutsches
1131 Zentrum für Luft- und Raumfahrt, the Helmholtz Alliance for Astroparticle
1132 Physics funded by the Initiative and Networking Fund of the Helmholtz
1133 Association (Germany), by Slovak Academy of Sciences MVTs JEM-EUSO
1134 as well as VEGA grant agency project 2/0132/17, by National Science

1135 Centre in Poland grant (2015/19/N/ST9/03708), by Mexican funding agencies
1136 PAPIIT-UNAM, CONACyT and the Mexican Space Agency (AEM), and by
1137 State Space Corporation ROSCOSMOS and Russian Foundation for Basic
1138 Research (grant 16-29-13065). The authors acknowledge strong support
1139 from CNES who provided, besides funding, the leadership that made the
1140 EUSO-Balloon mission possible in a very short time. We are indebted to
1141 the balloon division of CNES for a perfect launch smooth flight operation
1142 and flawless telemetry. The Canadian Space Agency has provided outstanding
1143 facilities at the Timmins Stratospheric Balloon Base and a quick and careful
1144 recovery of the instrument. We would like to thank our laboratories in the
1145 collaboration and the former collaborators for their strong and undivided
1146 support all along this project.

1147 **References**

- 1148 [1] B.R. Dawson, M. Fukushima and P. Sokolsky, *Prog. Theor. Exp. Phys.*, 12
1149 (2017) 12A107.
1150 <https://doi.org/10.1093/ptep/ptx054>
- 1151 [2] F. Fenu et al., in *Proc. of 35th Int. Cosmic Ray Conf. (Busan; 2017)*,
1152 Pos (ICRC2017) 486.
1153 <https://pos.sissa.it/301/486/pdf>
- 1154 [3] D. Ivanov, in *Proc. of 34th Int. Cosmic Ray Conf. (The Hague; 2015)*,
1155 Pos (ICRC2015) 349.
1156 <https://pos.sissa.it/236/349/pdf>
- 1157 [4] D. Ivanov, in *Proc. of 35th Int. Cosmic Ray Conf. (Busan; 2017)*,
1158 Pos (ICRC2017) 496.
1159 <https://pos.sissa.it/301/496/pdf>
- 1160 [5] I. Allekotte et al., *Nucl. Instrum. Meth. A* 586 (2007) 409.
1161 <https://doi.org/10.1016/j.nima.2007.12.016>

- 1162 [6] T. Abu-Zayyad et al., Nucl. Instrum. Meth. A 689 (2017) 87.
1163 <http://dx.doi.org/10.1016/j.nima.2012.05.079>
- 1164 [7] The Pierre Auger Collaboration, Science 357 (2017) 1266.
1165 <https://doi.org/10.1126/science.aan4338>
- 1166 [8] The Telescope Array Collaboration (R.U. Abbasi et al.), Astrophys. J. Lett.
1167 790 (2014) L21.
1168 <http://doi.org/10.1088/2041-8205/790/2/L21>
- 1169 [9] R.U. Abbasi et al., Astrophys. J. 862 (2018) 92.
1170 <https://doi.org/10.3847/1538-4357/aac9c8>
- 1171 [10] J. Albraham et al., Nucl. Instrum. Meth. A 620 (2010) 227.
1172 <https://doi.org/10.1016/j.nima.2010.04.023>
- 1173 [11] H. Tokuno et al., Nucl. Instrum. Meth. A 676 (2012) 54.
1174 <https://doi.org/10.1016/j.nima.2012.02.044>
- 1175 [12] B. Keilhauer et al., EPJ Web Conf. 53 (2013) 01010.
1176 <https://doi.org/10.1051/epjconf/20135301010>
- 1177 [13] R. Benson and J. Linsley, in Proc. 17th Int. Cosmic Ray Conference, 8
1178 (1981; Paris) 145.
1179 <http://adsabs.harvard.edu/abs/1981ICRC....8..145B>
- 1180 [14] R.E. Streitmatter et al. (the OWL Study Collaboration), AIP Conf. Proc.,
1181 433 (1998) 95.
1182 <https://doi.org/10.1063/1.56149>
- 1183 [15] C.N. De Marzo (the Airwatch Collaboration), AIP Conference Proceedings,
1184 433 (1998) 87.
1185 <https://doi.org/10.1063/1.56140>
- 1186 [16] O. Catalano et al., in P.A. Shaver, L. DiLella, A. Giménez
1187 (eds.); “Astronomy, Cosmology and Fundamental Physics”, ESO
1188 ASTROPHYSICS SYMPOSIA (2003), 427.

- 1189 [17] The JEM-EUSO Collaboration (J.H. Adams Jr. et al.), *Exp. Astron.* 40
1190 (2015) 117.
1191 <https://doi.org/10.1007/s10686-014-9376-3>
- 1192 [18] The JEM-EUSO Collaboration (J.H. Adams Jr. et al.), *Exp. Astron.* 40
1193 (2015) 153.
1194 <https://doi.org/10.1007/s10686-013-9371-0>
- 1195 [19] The JEM-EUSO Collaboration (J.H. Adams Jr. et al.), *Exp. Astron.* 40
1196 (2015) 183.
1197 <https://doi.org/10.1007/s10686-014-9427-9>
- 1198 [20] P.A. Klimov et al., *Space Sci. Rev.* 212 (2017) 1687.
1199 <https://doi.org/10.1007/s11214-017-0403-3>
- 1200 [21] The JEM-EUSO Collaboration (J.H. Adams Jr. et al.), *Exp. Astron.* 40
1201 (2015) 1 and the articles in the same issue ‘Special Issue on the JEM-EUSO
1202 Mission’.
1203 <http://doi.org/10.1007/s10686-015-9483-9>
- 1204 [22] J.H. Adams Jr. et al., *Astropart. Phys.* 44 (2013) 76.
1205 <https://doi.org/10.1016/j.astropartphys.2013.01.008>
- 1206 [23] M. Casolino et al., in *Proc. of 35th Int. Cosmic Ray Conf. (Busan; 2017)*,
1207 Pos (ICRC2017) 368.
1208 <https://pos.sissa.it/301/368/pdf>
- 1209 [24] P. Klimov et al., in *Proc. of 35th Int. Cosmic Ray Conf. (Busan; 2017)*,
1210 Pos (ICRC2017) 412.
1211 <https://pos.sissa.it/301/412/pdf>
- 1212 [25] A. Olinto et al., in *Proc. of 35th Int. Cosmic Ray Conf. (Busan; 2017)*,
1213 Pos (ICRC2017) 542.
1214 <https://pos.sissa.it/301/542/pdf>

- 1215 [26] G. Abdellaoui et al., Nucl. Instrum. Meth. A 866 (2017) 150.
1216 <https://doi.org/10.1016/j.nima.2017.05.043>
- 1217 [27] J. Bayer et al., in Proc. of 33rd Int. Cosmic Ray Conf. (Rio de Janeiro;
1218 2013) ID0432. (preprint) In ‘The JEM-EUSO Mission: Contributions to
1219 the ICRC2013’, arXiv:1307.7071.
- 1220 [28] E.g. World Data Center for Geomagnetism, Kyoto University; Geomagnetic
1221 Equatorial Dst index Home Page.
1222 <http://wdc.kugi.kyoto-u.ac.jp/dst/dir/> (accessed on July 25, 2018).
- 1223 [29] V.Y. Khomich, A.I. Semenov and N.N. Shefov; Airglow as an Indicator
1224 of Upper Atmospheric Structure and Dynamics, Springer-Verlag GmbH,
1225 Heidelberg (2008).
1226 ISBN 978-3-540-75833.
1227 <http://www.springer.com/la/book/9783540758327>
- 1228 [30] G.G. Shepherd et al., J. Atmos. Sol.-Terr. Phys., 68 (2006) 2000.
1229 <http://doi.org/10.1016/j.jastp.2006.06.006>
- 1230 [31] A.V. Dmitriev et al., Planet. Space Sci. 59 (2011) 733.
1231 <http://doi.org/10.1016/j.pss.2011.02.010>
- 1232 [32] P. Bobik et al., in Proc. of 33rd Int. Cosmic Ray Conf. (Rio de Janeiro;
1233 2013) ID0874. (preprint) In ‘The JEM-EUSO Mission: Contributions to
1234 the ICRC2013’, arXiv:1307.7071.
- 1235 [33] C. Leinert et al., Astron. Astrophys. Suppl. Ser. 127 (1998) 1.
1236 <http://doi.org/10.1051/aas:1998105>
- 1237 [34] O. Catalano et al., Nucl. Instrum. Meth. A480 (2002) 547.
1238 [http://doi.org/10.1016/S0168-9002\(01\)00958-5](http://doi.org/10.1016/S0168-9002(01)00958-5)
- 1239 [35] S. Giarrusso et al., in Proc. of 28th Int. Cosmic Ray Conf. (Tsukuba) 2
1240 (2003) 849.
1241 <http://www-rccn.icrr.u-tokyo.ac.jp/icrc2003/PROCEEDINGS/PDF/212.pdf>

- 1242 [36] L.M. Barbier et al., *Astropart. Phys.* 22 (2005) 439.
1243 <http://doi.org/10.1016/j.astropartphys.2004.10.002>
- 1244 [37] N. Sakaki, et al., in *Proc. of 30th Int. Cosmic Ray Conf. (Merida)*, 5 (2007)
1245 965.
1246 <http://indico.nucleares.unam.mx/event/4/session/39/contribution/497/material/paper/0.pdf>
- 1247 [38] P. Sokolsky, *AIP Conference Proceedings*, 433 (1998) 65.
1248 <https://doi.org/10.1063/1.56147>
- 1249 [39] R.M. Baltrusaitis et al., *Nucl. Instrum. Meth.*, A240 (1985) 410.
1250 [https://doi.org/10.1016/0168-9002\(85\)90658-8](https://doi.org/10.1016/0168-9002(85)90658-8)
- 1251 [40] G.K. Garipov et al., *Astropart. Phys.* 24 (2005) 400.
1252 <https://doi.org/10.1016/j.astropartphys.2005.09.001>
- 1253 [41] The JEM-EUSO Collaboration (J.H. Adams Jr. et al.), *Exp. Astron.*
1254 40 (2015) 281.
1255 <http://doi.org/10.1007/s10686-015-9467-9>
- 1256 [42] P. von Ballmoos et al., in *Proc. of 34th Int. Cosmic Ray Conf. (The Hague;*
1257 *2015)*, Pos (ICRC2015) 322.
1258 <https://pos.sissa.it/236/322/pdf>
- 1259 [43] J. Evrard et al., in *Proc. of 22nd ESA Symp. on European Rocket and*
1260 *Balloon Programmes (Tromso, Norway; 2015)*, 217.
1261 ISBN 978-92-9221-294-0. ISSN 1609-042X., p.217
- 1262 [44] JEM-EUSO Collaboration (Y. Takizawa and J.H. Adams), in *Proc. of*
1263 *30th Int. Cosmic Ray Conf. (Merida)*, 5 (2007) 1033.
1264 <http://indico.nucleares.unam.mx/event/4/session/39/contribution/823/material/paper/0.pdf>
- 1265 [45] Y. Takizawa et al., in *Proc. of 31st Int. Cosmic Ray Conf. (Lodz; 2009)*,
1266 ID792.
1267 <http://icrc2009.uni.lodz.pl/proc/pdf/icrc0792.pdf>

- 1268 [46] K. Maekawa et al., in Proc. of 31st Int. Cosmic Ray Conf. (Lodz; 2009),
1269 ID103.
1270 <http://icrc2009.uni.lodz.pl/proc/pdf/icrc0103.pdf>
- 1271 [47] The JEM-EUSO Collaboration (J.H. Adams Jr. et al.), Exp. Astron. 40
1272 (2015) 19.
1273 <http://doi.org/10.1007/s10686-014-9418-x>
- 1274 [48] Hamamatsu Photonics K.K.; ‘PHOTOMULTIPLIER TUBES AND
1275 PHOTOMULTIPLIER TUBE ASSEMBLIES R11265U SERIES / H11934
1276 SERIES’
1277 https://www.hamamatsu.com/resources/pdf/etd/R11265U_H11934.TPMH1336E.pdf
1278 (accessed on July 31, 2017).
- 1279 [49] The JEM-EUSO Collaboration (J.H. Adams Jr. et al.), Exp. Astron. 40
1280 (2015) 91.
1281 <https://doi.org/10.1007/s10686-015-9453-2>
- 1282 [50] Schott AG; ‘BG3 filter data sheet (Status December 12, 2014)’.
1283 https://www.schott.com/d/advanced_optics/71957ac1-e196-4963-b006-b2ad1830bf2f/1.5/schott-bandpass-bg3-jun-2017-en.pdf
1284 (accessed on July 25, 2018).
- 1285 [51] M. Unger, B.R. Dawson, R. Engel, F. Schussler and R. Ulrich,
1286 Nucl. Instrum. Meth. A588 (2008) 433.
1287 <https://doi.org/10.1016/j.nima.2008.01.100>
- 1288 [52] The JEM-EUSO Collaboration (J.H. Adams Jr. et al.), Exp. Astron. 40
1289 (2015) 135.
1290 <http://doi.org/10.1007/s10686-014-9377-2>
- 1291 [53] V. Scotti and G. Osteria, J. Inst. 9 (2014) C03034.
1292 <https://doi.org/10.1088/1748-0221/9/03/C03034>
- 1293 [54] C. Moretto et al., in Proc. of 34th Int. Cosmic Ray Conf. (The Hague;
1294 2015), Pos (ICRC2015) 655.
1295 <https://pos.sissa.it/236/655/pdf>

- 1296 [55] S. Dagoret-Campagne et al., in Proc. of 34th Int. Cosmic Ray Conf. (The
1297 Hague; 2015) Pos (ICRC2015) 607.
1298 <https://pos.sissa.it/236/607/pdf>
- 1299 [56] The JEM-EUSO Collaboration (Y. Kawasaki), in Proc. of 30th Int. Cosmic
1300 Ray Conf. (Merida), 7 (2007) 1037.
1301 <http://indico.nucleares.unam.mx/event/4/session/39/contribution/824/material/paper/0.pdf>
- 1302 [57] NOAA National Center for Environmental Information; ‘Defense
1303 Meteorological Satellite Program (DMSP) data’.
1304 <https://ngdc.noaa.gov/eog/dmsp.html> (accessed on March 14, 2015).
- 1305 [58] C. Catalano; *Premières lumières du télescope EUSO-Balloon Vers la*
1306 *détection des rayons cosmiques ultra-énergétiques depuis l’espace* (in
1307 French; First light of the EUSO-Balloon telescope: toward the detection of
1308 ultra-high energy cosmic rays from space); PhD Dissertation, *l’Université*
1309 *Toulouse 3 Paul Sabatier*, France (2015).
1310 <https://tel.archives-ouvertes.fr/tel-01417298>
- 1311 [59] G. Abedellaoui et al., J. Inst., 13 (2018) P05023.
1312 <http://stacks.iop.org/1748-0221/13/i=05/a=P05023>
- 1313 [60] G. Osteria et al., in Proc. of 34th Int. Cosmic Ray Conf. (The Hague; 2015)
1314 Pos (ICRC2015) 659.
1315 <https://pos.sissa.it/236/659/pdf>
- 1316 [61] C. Catalano et al., in Proc. of 34th Int. Cosmic Ray Conf. (The Hague;
1317 2015) Pos (ICRC2015) 622.
1318 <https://pos.sissa.it/236/622/pdf>
- 1319 [62] S. Pomme, Appl. Radiat. Isot. 66 (2008) 941.
1320 <https://doi.org/10.1016/j.apradiso.2008.02.038>
- 1321 [63] C. Moretto; *Étude du fonctionnement d’un télescope de lumière de*
1322 *fluorescence dans le cadre du projet EUSO-Balloon* (in French; Study of

- 1323 a fluorescence telescope for the EUSO-Balloon project); PhD Dissertation,
1324 *l'Université Paris-Sud*, France (2016).
1325 <https://tel.archives-ouvertes.fr/tel-01239883>
- 1326 [64] C. Blasksley and P. Gorodezky, Nucl. Instrum. Meth. A 764 (2014) 198.
1327 <http://doi.org/10.1016/j.nima.2014.07.033>
- 1328 [65] B. Panico et al., in Proc. of 34th Int. Cosmic Ray Conf. (The Hague; 2015)
1329 Pos (ICRC2015) 667.
1330 <https://pos.sissa.it/236/667/pdf>
- 1331 [66] S. Agostinelli et al., Nucl. Instrum. Meth. A506 (2003) 250.
1332 [http://doi.org/10.1016/S0168-9002\(03\)01368-8](http://doi.org/10.1016/S0168-9002(03)01368-8)
- 1333 [67] Geant4 Collaboration; 'GEANT4: A toolkit for simulation of the passage
1334 of particles through matter'.
1335 <http://www.geant4.org/geant4/> (accessed on October 20, 2016).
- 1336 [68] S. Argirò et al., Nucl. Instrum. Meth. A580 (2007) 1485.
1337 <http://doi.org/10.1016/j.nima.2007.07.010>
- 1338 [69] Natural Resources Canada; 'online mapping tool for National Topographic
1339 System'.
1340 <http://atlas.gc.ca/toporama/en/> (January 6, 2017)
- 1341 [70] E.g. Google Maps; 'an online map service (satellite images for the region
1342 of interest are provided by DigitalGlobe).
1343 <https://www.google.ca/maps/place/Timmins,+ON/> (accessed on October
1344 20, 2016).
- 1345 [71] Earth Science Data Interface, University of Maryland; 'Landsat imagery
1346 covering Timmins region taken on August 26, 2009'.
1347 ftp://ftp.glcfc.umd.edu/glcfc/Landsat/WRS2/p021/r026/L5021026_02620090826.TM-GLS2010/
1348 (accessed on July 18, 2016).

- 1349 [72] Bing Maps: ‘Aerial image of Area (M)’ dated April 2016’.
1350 <https://www.bing.com/maps?osid=d1f6cbb9-c3d4-4732-8b5a-ee702aeb741&cp=48.67,-82.1&lvl=16&style=h>
1351 (accessed on May 21, 2017).
- 1352 [73] S. Bilin et al., “SPACIROC3: 100 MHz photon counting ASIC for
1353 EUSO-SPB”, Nucl. Instrum. Meth. A (in press)
1354 <https://doi.org/10.1016/j.nima.2017.12.060>
- 1355 [74] H. Dekker et al., in Proc. SPIE, Optical and IR Telescope Instrumentation
1356 and Detectors, 4008 (2000) 534.
1357 <http://doi.org/10.1117/12.395512>
- 1358 [75] European Southern Observatory; ‘UVES–Ultraviolet and Visual Echelle
1359 Spectrograph’.
1360 <http://www.eso.org/sci/facilities/paranal/instruments/uves.html>
1361 (accessed on August 15, 2016).
- 1362 [76] C. Emde et al., Geosci. Model Dev. 9 (2016) 1647.
1363 <http://doi.org/doi:10.5194/gmd-9-1647-2016>
- 1364 [77] B. Mayers et al.; ‘libRadtran website’.
1365 <http://www.libradtran.org/doku.php> (accessed on September 1, 2016).
- 1366 [78] A. Bucholtz, Appl. Opt. 34 (1995) 2765.
1367 <http://doi.org/doi:10.1364/AO.34.002765>
- 1368 [79] J.H. Seinfeld and S.N. Pandis; Atmospheric Chemistry and Physics: From
1369 Atmospheric Chemistry and Physics: From Air Pollution to Climate
1370 Change, 2nd Edition; John Wiley & Sons, Inc., Hoboken (2006).
1371 ISBN: 978-0-471-72018-8.
- 1372 [80] M. Conner; ‘Light spectrum/spectrometer charts and raw data for common
1373 lights’.
1374 <http://www.designingwithleds.com/light-spectrum-charts-data/> (accessed
1375 on October 3, 2017).

- 1376 [81] R.F. Pfaff Jr., *Space Sci. Rev.* 168 (2012) 23.
1377 <http://doi.org/10.1007/s11214-012-9872-6>
- 1378 [82] NASA Balloon Program Office; ‘NASA Code 820 (Super Pressure
1379 Balloon)’.
1380 <http://sites.wff.nasa.gov/code820/spb.html> (accessed on July 25, 2018).
- 1381 [83] L. Wiencke et al., in *Proc. of 35th Int. Cosmic Ray Conf. (Busan; 2017)*
1382 *Pos (ICRC2017)* 1097.
1383 <https://pos.sissa.it/301/1097/pdf>
- 1384 [84] F. Capel et al., “A high resolution detector for the study of terrestrial and
1385 cosmic UV emission from the International Space Station”, *Adv. Space*
1386 *Res.* (2017; in press).
1387 <https://doi.org/10.1016/j.asr.2017.08.030>
- 1388 [85] The JEM-EUSO Collaboration (J.H. Adams Jr. et al.), *Exp. Astron.* 40
1389 (2015) 301.
1390 <http://doi.org/10.1007/s10686-015-9441-6>
- 1391 [86] R.R. Meier, *Space Sci. Rev.* 58 (1991) 1.
1392 <http://doi.org/10.1007/BF01206000>
- 1393 [87] S. Perwitasari, *J. Geophys. Res.* 120 (2015) 9706.
1394 <http://doi.org/10.1002/2015JA021424>

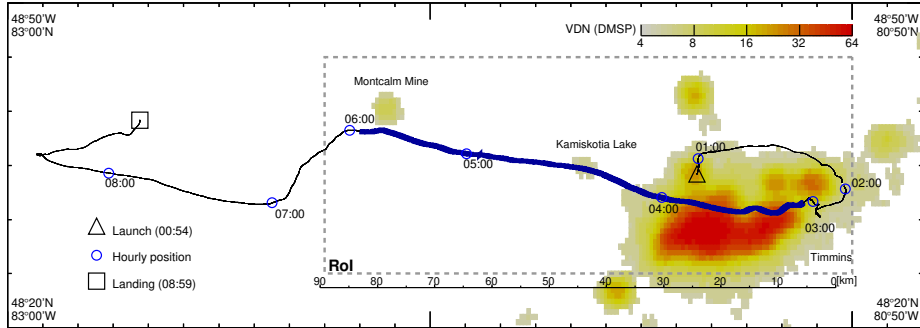


Figure 1: GPS ground track of the EUSO-Balloon optical axis shown by the solid curve. The VDN distribution is shown in color scale. A triangle and a square mark the launch and landing positions, respectively. The hourly positions are also marked by circles. The bold curve indicates the track during the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

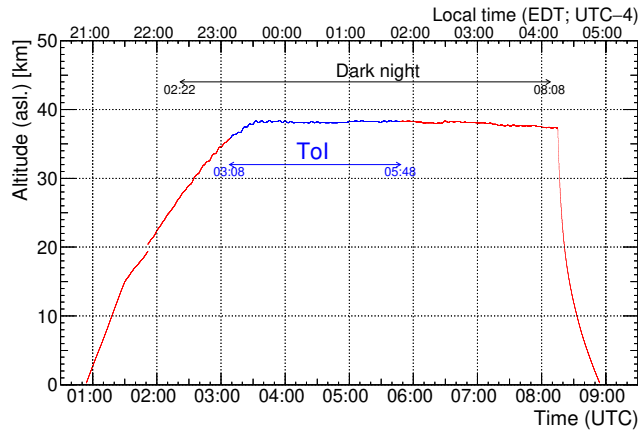


Figure 2: Altitude H_0 of the EUSO-Balloon telescope above sea level as a function of the UTC time t . The local EDT time is shown on the top. The upper and lower arrows indicate the dark night period and the ToI, respectively.

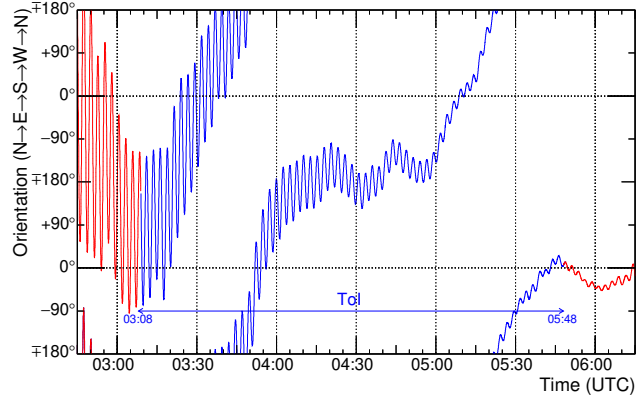


Figure 3: Orientation Φ_0 of the EUSO-Balloon telescope as a function of the time t . The arrow represents the ToI.

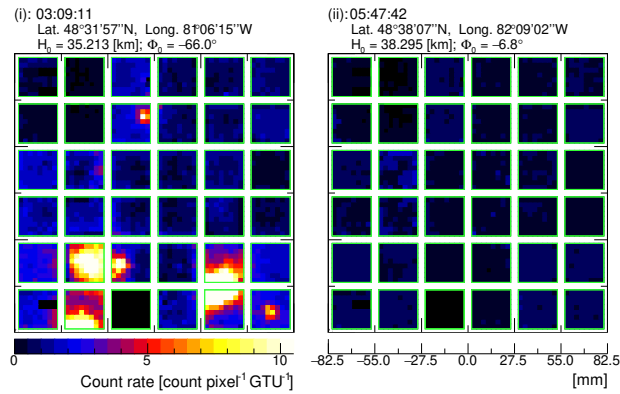


Figure 4: Examples of $\langle n \rangle$ values of all the pixels on the PDM for the packets acquired at (i) 03:09:11 and (ii) 05:47:42 on the left and right panels, respectively. Malfunctioning pixels are blackened out. The ground position of the EUSO-Balloon optical axis and the orientation of the 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.

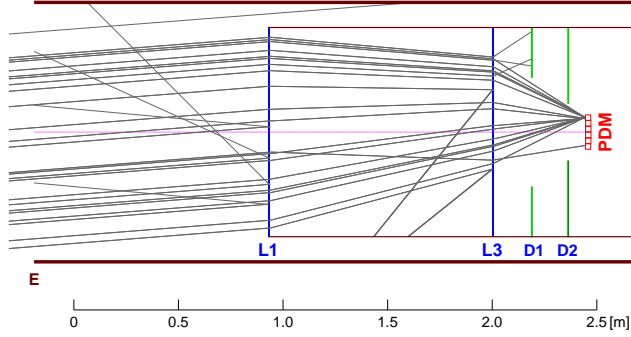


Figure 5: Selected examples of ray trace simulations for a point-like source at the incident off-axis direction $\vartheta = 4.5^\circ$. The configuration of the front (L1) and rear (L3) lenses, opening entrance (E), diaphragms (D1) and (D2) and the PDM is shown on the cross section of the EUSO-Balloon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

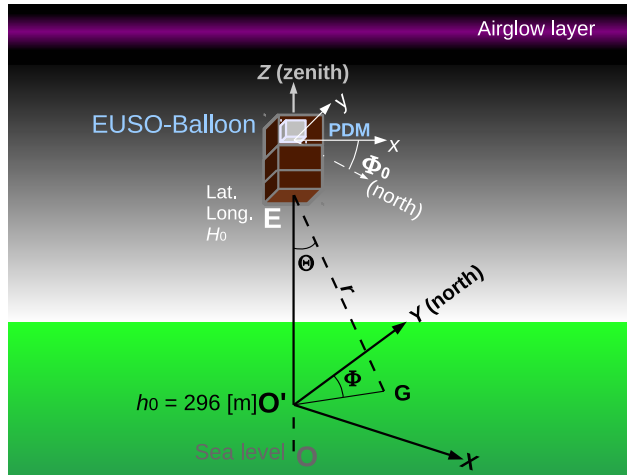


Figure 6: Geometry used in the analysis. The position of the EUSO-Balloon telescope is at Point E $(0, 0, H_0)$. In the direction of the nadir angle Θ and azimuth Φ , Point G (X, Y, h_0) is defined at the distance r from Point E. Point O' indicates the position of the optical axis on $h_0 = 296$ m asl. The orientation Φ_0 of the telescope is defined as illustrated.

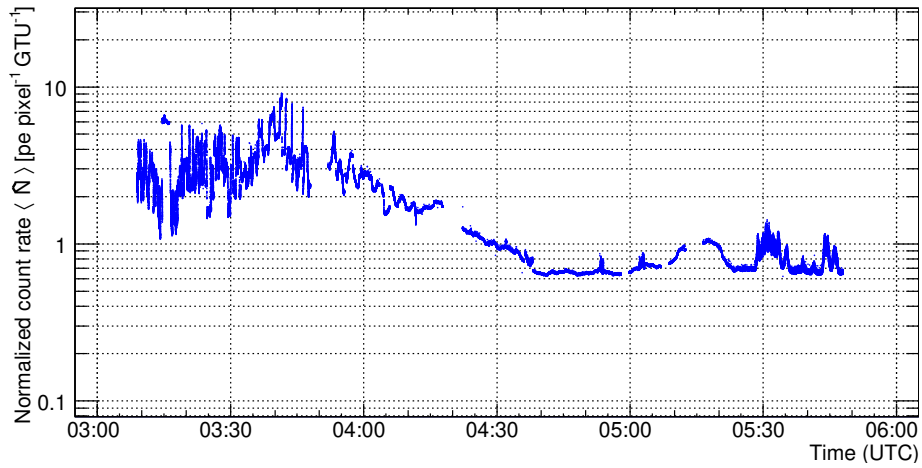


Figure 7: Average normalized count rates $\langle \tilde{N} \rangle$ as a function of the packet time t_m . Data are partly eliminated due to a temporary hardware problem around 04:17 and due to a transient instability of the electronics around 04:58 and 05:07. Interruptions starting at 03:47 and 05:13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

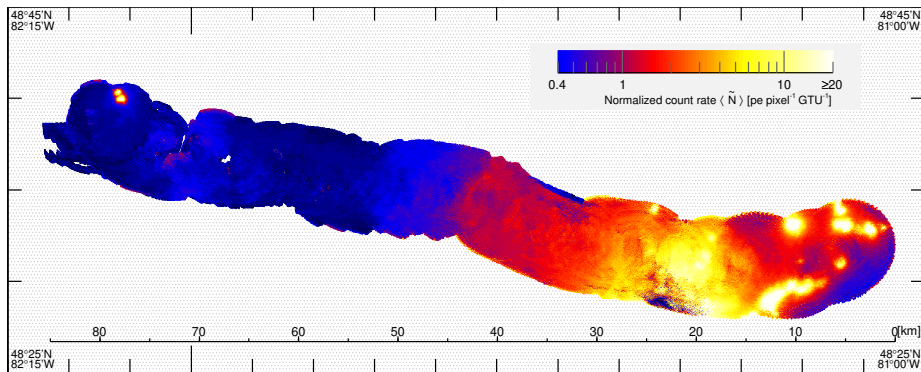


Figure 8: Normalized count rates $\langle \tilde{N} \rangle$ projected onto geographic coordinates. The shaded areas represent the area for which there is no determined $\langle \tilde{N} \rangle$ values. Coordinates on the corners are labeled together with ticks every 5' on both axes.

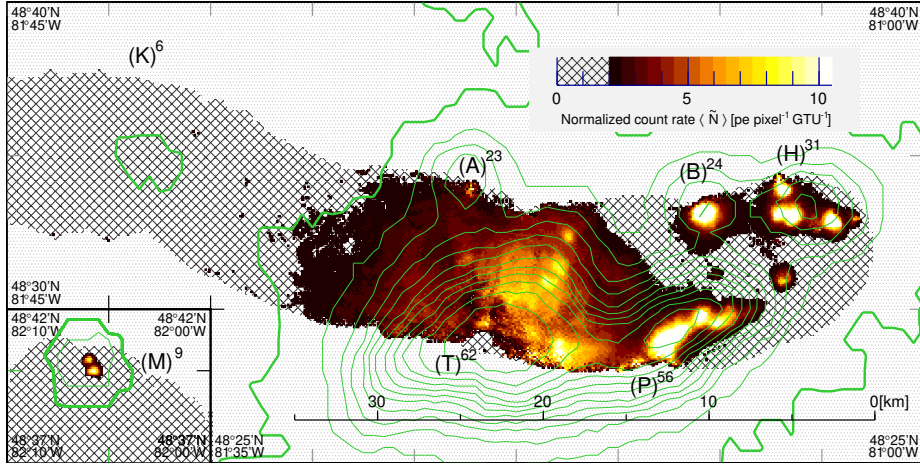


Figure 9: Extract from Fig. 8 shown with VDN contours overlaid, as in Fig. 1. The scales and resolutions have been modified. The hashed areas indicate the grid points with $\langle \tilde{N} \rangle < 1.5$ pe pixel⁻¹ GTU⁻¹. Bold contours are for VDN = 4 and thin ones are given at a step of 5. The local 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.

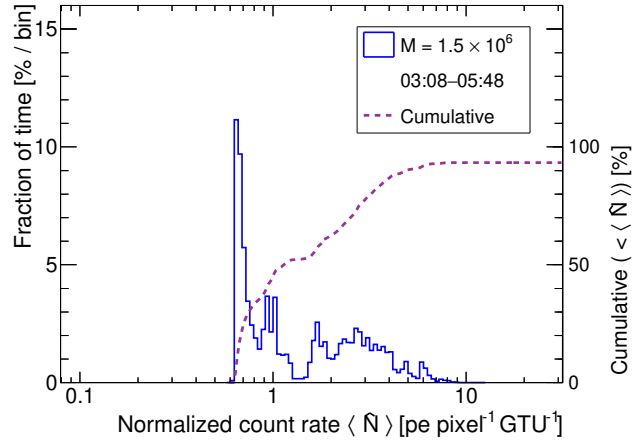


Figure 10: Temporal $\langle \tilde{N} \rangle$ distribution in terms of the packets with respect to the total $M = 1.5 \times 10^6$. The unity of the distribution is normalized to the ~ 2.5 hour time assigned for this work. The cumulative fraction below the given $\langle \tilde{N} \rangle$ value is shown by the dashed curve to the scale on the right.

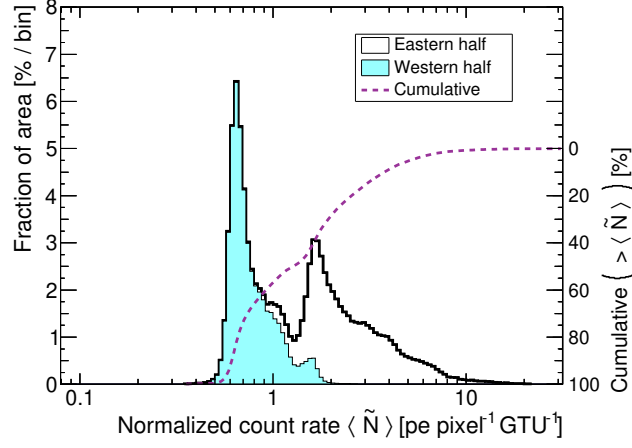


Figure 11: Areal $\langle \tilde{N} \rangle$ distribution in terms of the grid points with respect to the total $K = 3.8 \times 10^5$. The contributions from eastern and western halves whose areas are even are displayed by the clear and filled parts of the histogram, respectively. The cumulative fraction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

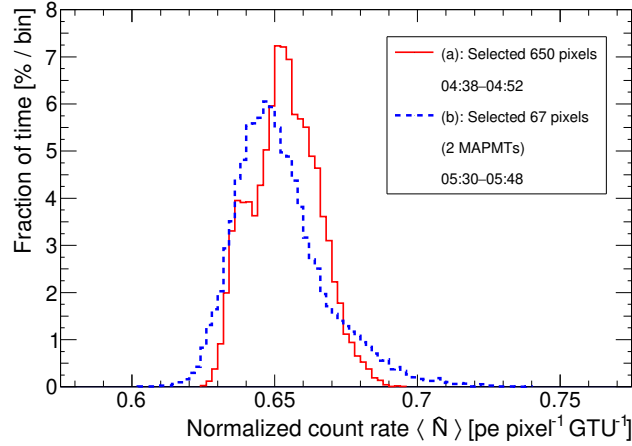


Figure 12: $\langle \tilde{N} \rangle$ distributions for Case (a) of the active pixels between 04:38 and 04:52 and Case (b) of those from more strictly selected 67 pixels between 05:30 and 05:48 shown as the solid and dashed histograms, respectively. Each histogram is normalized to the total number of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

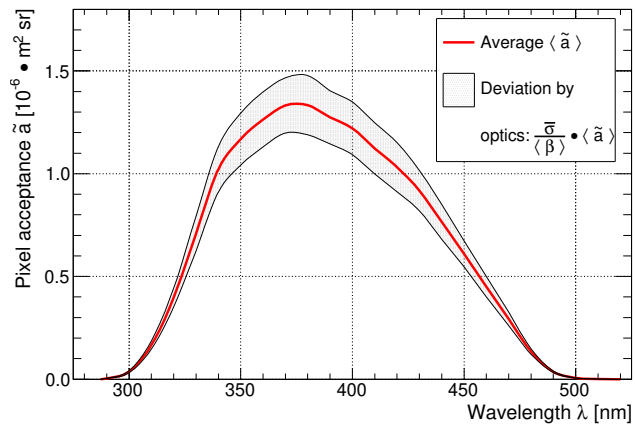


Figure 13: Average pixel acceptance $\langle \tilde{a} \rangle$ over the selected 650 pixels to diffuse light as a function of the wavelength λ . The shaded interval indicates the SD component, $(\bar{\sigma} / \langle \bar{\beta} \rangle) \cdot \langle \tilde{a} \rangle$ over these pixels due to the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