Possible Thunderstorm Flashes Measured by AURA-2 Detector on Board DEKART Satellite

Konstantin D. Shchelkanov, Dmitry V. Chernov, Evgeny V. Glinkin, Pavel A. Klimov, and Alexey S. Murashov

Abstract Since 2018, Skobeltsyn Institute of Nuclear Physics of Moscow State University has developed a series of compact UV detectors for space missions called AURA (AURA−Atmospheric Ultraviolet RAdiation). The purpose of the experiment is to observe the glow of the night atmosphere. The main feature of these detectors is the use of silicon photomultipliers (SiPM), which have small size, low supply voltage, and high reliability. It makes these photo sensors suitable for use on board nano satellites. The second detector in the AURA series, the AURA-2, currently operates on board the DEKART satellite. This detector version has a higher time resolution (10 ms) and wider field of view (22 × 90°) in comparison with the AURA-1 detector used on board the VDNH-80 satellite. Two successful sessions of measurements of the night atmosphere emission were carried out: in September and December 2021, respectively. Several fast UV flashes were detected. They were registered northeast of Papua New Guinea, and their characteristic duration was tens of milliseconds. Analyses of cloud coverage and lighting location networks data suggest a thunderstorm origin of these flashes.

Keywords Orbital UV detector · Cubesat · Silicon photomultiplier

1 Introduction

Ultraviolet glow in the Earth's atmosphere occurs due to a variety of phenomena differing in terms of source and mechanism of occurrence. Phenomena can be divided into two groups: quasi-stationary and transient. Quasi-stationary phenomena include: atmospheric airglow, scattered light of the moon and stars, anthropogenic sources,

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auroral oval emissions. Transient events originate from lightning discharges, upper atmosphere transient luminous events (TLEs), and effects from penetrating energetic particles into the Earth's atmosphere.

Quasi-stationary atmospheric emission was previously studied in a numerous space-based experiments. In 1975, the TAIYO satellite was launched from Japan with two middle UV radiometers (MUV) and four vacuum ultraviolet photon counters (GUV) on board. UV radiometers based on photomultiplier tubes were developed to measure the global distribution of the atmospheric albedo of solar radiation at 2550 and 2900 Å. Each of the four GUV counters had a filter in its composition to highlight a certain range of wavelengths. Such as 304 A of He + emissions, 584 Å of He emissions, 833 Å of O + emissions and 1026 Å of H emissions [1]. Since 2002, the GUVI (Global Ultraviolet Imager) instrument has been operating on board the TIMED satellite. This is a spatial scanning ultraviolet spectrometer that gives a map of the atmospheric glow in five wavelength intervals (121.6, 130.4, 135.6, 140−150 and 165−180 nm) [2]. On board the Soviet satellites KOSMOS-45 and KOSMOS-215 one of the first measurements of Earth UV airglow and scattered solar emission were conducted [3, 4]. In the second one the emission of equatorial ionosphere anomaly was observed for the first time.

The study of thunderstorm activity has long captured the attention of atmospheric scientists but the first TLEs were measured only in 1989. It was proved experimentally that thunderstorms are not limited to ordinary lightning, and affect almost the entire atmosphere up to the mesosphere [5]. These phenomena are classified into several types (sprites, blue jets, halo, gigantic jets, ELVES). The observed processes are flashes of electromagnetic radiation in a wide wavelength band lasting from hundreds of microseconds (ELVES) to several hundred milliseconds (gigantic jets). The characteristic sizes reach tens of kilometers in height and tens and in some cases hundreds of kilometers in horizontal directions.

Sprites are weak in intensity but large in size flashes of electromagnetic radiation. They appear above clouds at heights of 50–90 km in a few tens of milliseconds after, most often, positive cloud-to-ground (CG) lightning discharges. Sprites, commonly, have a duration of several tens of milliseconds, but both short phenomena (~1–10 ms) and long ones (~150–200 ms) have been observed [6]. At their top, sprites emit in the red part of the spectrum but as they descend in the atmosphere, the radiation of the second positive nitrogen system ($2PN_2$) begins to dominate, and the color changes from red to purple, and then to blue and light blue. Sprites often appear in groups and rarely as single events. The total length of the sprites reaches 50 km, and the cross-sectional dimensions are 5–30 km [7].

Blue jets are rising electromagnetic flashes of predominantly blue color, appearing only over very active thunderclouds (up to several discharges per second). The jets were first discovered in 1990, and their existence was confirmed in 1994 in an the Sprite94 experiment [8]. They occur at lower altitudes than sprites (~15–20 km). Jets have a cone-shaped structure, with the base pointing upward, and the angle at the apex of the cone averages 15°. The cone can reach a height of 40 km, and propagates at a speed of about 100 km/sec. The duration of a typical jet is about 200 ms [9].

Another TLE type, called blue starters, are very similar in appearance to blue jets, but are much brighter and shorter. They are only a few kilometers long and travel up to a height of about 25 km. The speed of propagation varies from a few tens, to 150 km/sec. Images from the FORMASAT-2 satellite made it possible to estimate the lifetime of the starters (60–90 ms), and the spatial dimensions, which were about 8 km in height and about 3 km in cross-section [10].

Elves (ELVES-Emission of Light and Very Low Frequency perturbations due to Electromagnetic Pulse Sources) are very fast phenomena with a characteristic lifetime of less than 1 ms. They are expanding ring-shaped red structures occuring in the lower ionosphere at an altitude of about 80–100 km. A typical ELVE can reach 200–700 km in diameter. Usually, ELVES are a consequence of a powerful electromagnetic pulse (EMP) arising from a cloud-to-ground lightning discharge or intracloud discharge [11].

In 2003, during a thunderstorm over the South China Sea so called gigantic jets were registered for the first time. These are the largest, longest and rarest transient phenomena. Like blue jets, they are formed at an altitude of about 20 km above active thunderstorm regions, but their length is almost 2 times greater, reaching 60–80 km. Thus, they directly connect the cloud and the lower layers of the Earth's ionosphere. Their duration is about 500 ms. The structure of a giant jet can be divided into two parts. The lower part, resembles an ordinary blue jet which spreads up to a height of 35–50 km [1], the upper part is reddish and resembles a sprite.

Global measurements of these phenomena are possible only on board the satellite. One of the most successful TLE research missions was the ISUAL experiment aboard the FORMOSAT-2 satellite [12]. A number of projects have been implemented at SINP MSU since 2005 (Universitetsky-Tatyana-1 [13], Universitetsky-Tatyana-2 [14], Vernov [15], Lomonosov [16] satellites). Use of nanosatellites for scientific experiments and observations is actively developing now. This makes it possible to deliver the equipment into orbit in a short time, but requires creation of universal, compact and low-consuming equipment. In this paper we briefly describe the new AURA-2 photometer based on silicon photomultipliers and report first results of atmospheric flashes measurements on board the DEKART satellite.

2 UV Detector AURA-2

Skobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University develops a series of compact detectors AURA (Atmospheric Ultraviolet RAdiation) [17] aimed to work out the use of silicon photomultipliers (SiPM) in open space. The first detector was launched on board the VDNH-80 satellite and had 4 channels with the same field of view (±22.5°) directed to nadir and 1 s temporal resolution. This detector was measuring the near-UV atmospheric emission (300–400 nm). The second detector in this series, named AURA-2, has an improved field of view (20° × 90°) and better temporal resolution (10 ms). The FOVs of two central SiPMs are the same (22.5°) and directed to nadir. The edge SiPMs are directed at an angle in the direction perpendicular to the satellite's velocity vector. This results in a wide (90°) field of view. Two filters are used in the central detectors, UFS-1 and FF01-375/110. These filters have different transmittance (UFS-1 transmits both in the near UV range (300–400 nm) and in the red wavelength range (600–800 nm), while FF01-375/110 only in the near UV) which allows to estimate ratio of emission in these bands.

The device uses Onsemi (USA) MicroFC-60035-SMT model SiPMs with the working area of 6 × 6 mm, and spectral sensitivity from 300 to 800 nm. Spectral sensitivity maximum is at 420 nm. This sensitivity is achieved at a supply voltage between anode and cathode of about 29.5 V. The digital thermometer Analog Devices (Malaysia) DS1631AU allows to control temperature and to take it into account during data processing. The 3D model and block diagram of the instrument are shown in Fig. 1.

A processor module based on the STmicroelectronics (Switzerland) STM32F722RET microcontroller is used to control the device power supply, digitize and process signals from SiPMs and store data. This model is faster than that used in AURA-1 increasing the temporal resolution up to 10 ms.

Photon fluxes are registered by measuring the current passing through the SiPMs with MAX9611 chips designed on the basis of current amplifiers and 12-bit analog-to-digital converters. The microcircuits have three signal amplification modes: × 1, × 4 and × 8. This allows measurements in a wide range of intensities, from the night sky to direct sunlight. The detector passed preflight calibrations [18].

Calibration measurements were performed using an LED with a wavelength of 405 nm and a precise Ophir (Israel) LaserStar light emission power meter. The LED was placed on one of the ports of the integrating sphere. On the second port of the sphere a narrow collimator is installed, which has a diameter of the exit hole of 1 mm and forms a uniform illumination of the SiPM surface within a radius of 5 mm. Simultaneously with measurements of the SiPM, the radiation intensity is registered by the NIST photodiode connected to the Ophir power meter. The equipment was located inside a black box in order to avoid additional radiation to the SiPMs. The dark current was determined before the calibration measurements. Measurements of the detector response were conducted in a wide range of incoming photon flux to

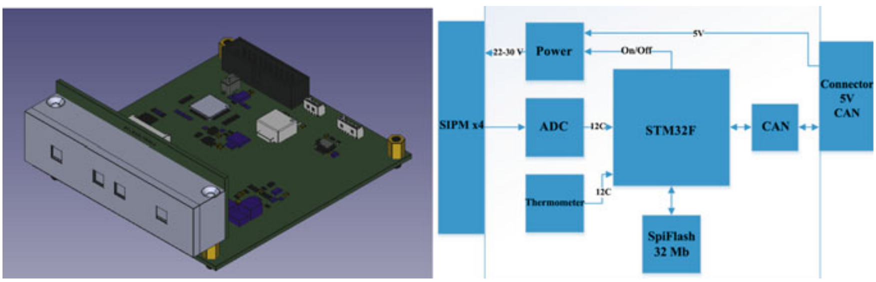

Fig. 1 3D model and block diagram of the AURA-2 detector electronics

obtain a calibration curve in the whole range of possible circumstances during space mission.

3 Results of AURA-2 Detector Measurements

The detector AURA-2 was launched and started operation in September 2020 as a part of the nano-satellite DECART payload. Two successful measurement sessions were carried out: in September and December 2021, respectively. The results of these sessions data analysis are presented in this section.

3.1 Measurement Session 13.09.2021

The first measurement session was conducted on September 13, 2021. AURA was turned on at 09:56 UTC over the islands just west of Greenland, and the measurements finished at 10:45 over Antarctica. After measurements began, the satellite was illuminated by the Sun for 7 min, then it crossed the terminator and was in the Earth's shadow for 35 min, then it was back on the day side and the measurements finished. The intensity of the glow measured during the night part of the orbit along the satellite trajectory is shown in Fig. 2. The intensity is obtained using the calibration curves measured before flight. At the beginning and at the end of the measurements, regions of high intensities of the order of 10^{10} photons per second are observed, which correspond to measurements on the day side. The large fluctuation of the signal on the daytime part of the orbit is explained by the constant switching of the measurement modes due to the large variability and large intensity of the glow.

Between 10:03 UTC and 10:36 UTC the signal intensity decreases monotonously, corresponding to the night part of the measurement. During this measurement session, the detector operated in the temperature range from –6 to 11 °C. Since SiPM have a dependence of the dark current on temperature, and the satellite is naturally cooled in the shadow of the Earth, we can assume that this decline is associated with a decrease in noise as the detector is cool. The comparison of current and temperature measured near the SiPMs is shown in Fig. 3. On the right plot a linear dependence is seen demonstrating an obvious correlation between the current and temperature. The correlation coefficient for the dependence of the average current on temperature is 0.986. Thus, the general trend is totally explained by the temperature, and the local variations (deviations from the linear dependence) are changes in the intensity of atmospheric glow.

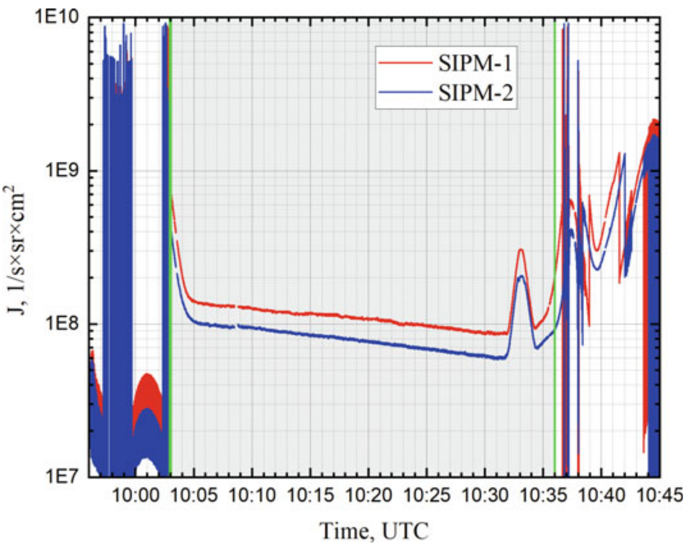

Fig. 2 The intensity of atmospheric emission measured by the detector along the satellite trajectory on September 13, 2021. Green lines mark when the satellite intersects the terminator

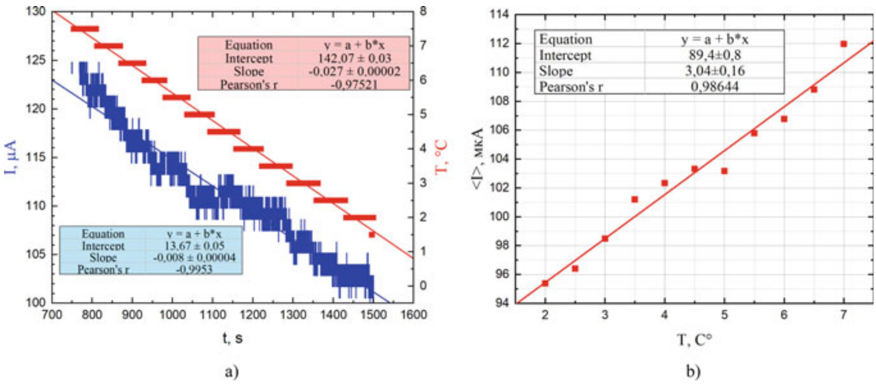

Fig. 3 Comparison of the temperature trend and signal **a** and dependence of average current on temperature **b** for measurements on 13.09.2021

3.2 Measurement Session 09.12.2021

On December 09, 2021 the second session of measurements was carried out. The duration was about 1 h. The measurements began at 13:58 UTC just west of Alaska on the night side and ended on the day side. Processing of the signal in terms of ADC (analog-to-digital converter) units was carried out in the same way as in the previous session. The satellite trajectory and intensity plots are shown in Fig. 4.

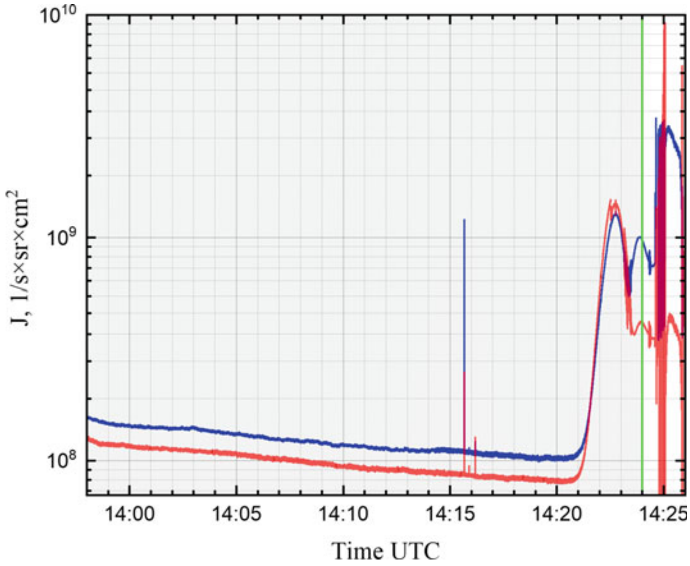

Fig. 4 The intensity of atmospheric emission measured by the detector along the satellite trajectory on 09.12.2021

The general character of these measurements coincides with the September measurements, intensity decreases monotonously at the night side and increases by more than an order of magnitude upon crossing to the day side. During the detector operation, the satellite moved over the Pacific Ocean and Australia. The same correlation between the temperature and the count rate is observed. The main difference between these measurements and the September session is the presence of short bright flashes in the second part of the nighttime orbit.

3.3 *Flashes*

During the analysis of the data obtained during the measurements of 09.12.2021, series of flashes with a typical duration of the order of tens of milliseconds were detected. They were recorded northeast of Papua New Guinea between 14:15 UTC and 14:18 UTC.

Three flashes (series of flashes) occurred in the field of view of the central channels SiPM-1 and 2 on which the filters were installed. The first flash was registered at 14:15:40, the coordinates of the satellite for this moment of time: –6.89°; 166.96°. The light curve of these flashes in the ADC codes is shown in Fig. 5. It shows the signals from the two central SiPMs. It is natural to assume that the first short and bright peak may be caused by the lightning return stroke, and other flashes are slower processes caused by this discharge (TLEs). The duration of the first peak cannot be

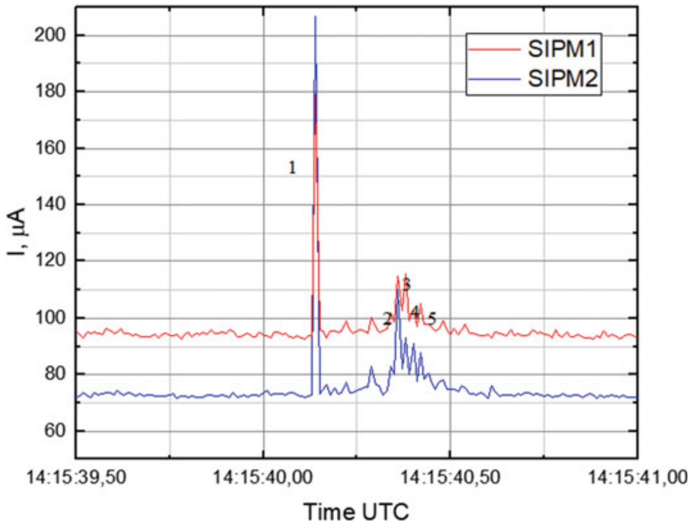

Fig. 5 The first series of flashes

estimated accurately because it is presented by a single high value in the otherwise continuous record with 10 ms resolution. The duration of the afterglow is about 130 ms and its temporal structure is represented by a number of flashes.

For a more detailed analysis, and in order to determine the nature of the events, the ratio of red-infrared (RI-radiation) to UV radiation was estimated. This ratio can be a measure of the altitude of discharge, as shown in [19] in the assumption of the spectrum of molecular nitrogen. The technique of estimation of RI/UV ratio is based on the fact that one of the filters (UFS-1) is actually transparent in the red range. Thus, if in the channel with UFS-1 there is a significant excess of the signal relative to the channel with the second filter, which at the same time passes better in the near-UV and totally opaque in red, it indicates a significant fraction of RI radiation. The following calculations were made to estimate RI/UV ratio. First, to determine the amplitudes of flashes the background levels I_0 were subtracted from the maximum ADC values. Second, the transparency of the filters in the UV and RI bands, as well as the quantum efficiency of the photomultipliers themselves for the same bands were taken into account. Thus, the RI/UV ratio can be estimated using the formula:

$$\frac{I_{RI}}{I_U} = \frac{(I_1 - \frac{k_{1U}}{k_{2U}} \cdot I_2)}{I_2} \cdot \frac{k_{2U} \cdot q_U}{k_{1R} \cdot q_R} \quad (1)$$

where I_1 and I_2–SiPM−1 and SiPM−2 signals, respectively; q_R and q_U–SiPM quantum efficiencies for RI-band to UV-band; k_{1R}, k_{1U}, and k_{2U}–the transparency coefficients of the UFS−1 filter in the RI and UV bands and the FF01-375/110 filter in the UV bands respectively; I_{RI} and I_U–the RI and UV signal components. The

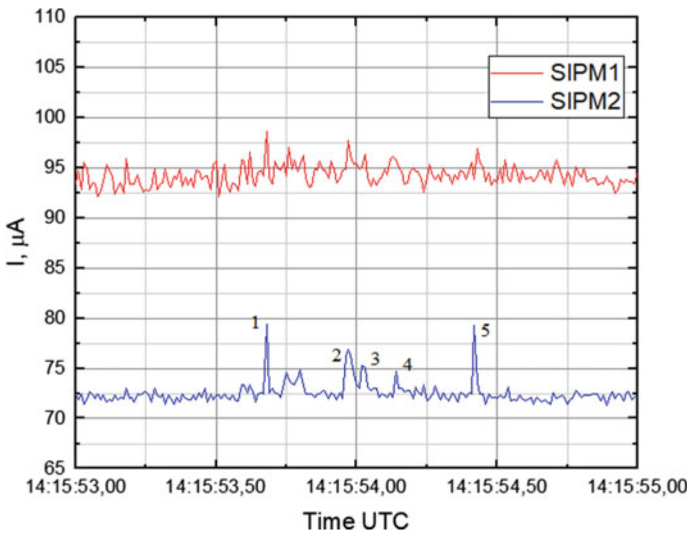

Fig. 6 The second series of flashes

quantum efficiencies of the SiPMs used in this estimate are ~0.37 for 320–430 nm and ~0.1 for RI-band.[1]

It is important to note that the described technique is valid only if the observed signal with a spectrum that in the UV part completely coincides with the bandwidth range of both filters. This can take place in the case of the sprite spectrum. For the first series of flashes only the third one has RI/UV ratio ~2, while for other flashes the ratio value is negative. This can be explained only by the additional signal in the part of FF01−375/110 filter transparency window where the UFS-1 is opaque (>400 nm). Thus, a more detailed modeling, taking into account lightning and TLEs spectrum should be done.

The second series of flashes was registered at 14:15:53 at the coordinates –7.7°; 166.79°. Its light curve is shown in Fig. 6. The very small intensities of these events relative to the background level in the first channel do not allow us to draw any significant conclusions regarding RI/UV ratio.

The third series of flashes was detected at 14:16:11 at the coordinates –8.77°; 166.57°. The signals measured by two channels are shown in Fig. 7.

For all flashes the RI/UV ratio is either negative or lies in the range 1–2. The first one most likely means that the flash corresponds to a lightning discharge, since the lightning spectrum contains lines in the UV region, but above 400 nm [20]. The

[1] The SiPM parameters are taken from the documentation: https://www.onsemi.com/pdf/datasheet/microc-series-d.pdf.

Filters transparency can be found here: FF01-375/110: https://www.idex-hs.com/store/products/products/semrock_optical_filters/individual_optical_filters.

UFS-1: http://elektrosteklo.ru/Elektrosteklo_Color_Glass_Spectral_Transmittance.pdf.

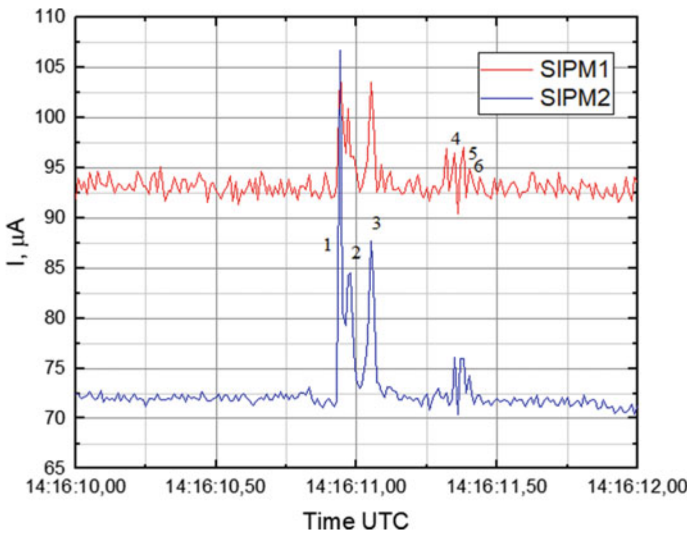

Fig. 7 The third series of flashes

second one corresponds to the discharge altitude of 50–60 km [21] in the assumption of molecular nitrogen sprite-like spectrum [22].

Finally, a joint analysis with ground-based lightning location networks and meteorological satellites data was performed. A map of cloud cover on the day of measurements was obtained from data of the Suomi NPP satellite operated by NOAA (National Oceanic and Atmospheric Administration) and it is presented in Fig. 8. The DEKART satellite trajectory is shown in Fig. 8. Also, from the website of the Blitzortung lightning detection network, a lightning map was taken for the right moment of time (Fig. 9). The green rectangle also marks the field of view of the detector.

In the FOV of the detector no powerful lightning strikes were measured by the ground-based networks. But their concentration in one place at one time close to the cloud coverage and quite powerful thunderstorm activity in this area indicate that recorded flashes are likely of thunderstorm origin.

4 Conclusions

The detector AURA-2 was launched and put into operation in 2020 as a part of the nano-satellite DEKART. Two complete measurement sessions were carried out in September and December 2021. The data of two measurement sessions were obtained and analyzed. The presence of correlation of monotonous decreasing of the signal on the night side with the temperature has been observed, which should be taken into account in further instrument operation and data processing.

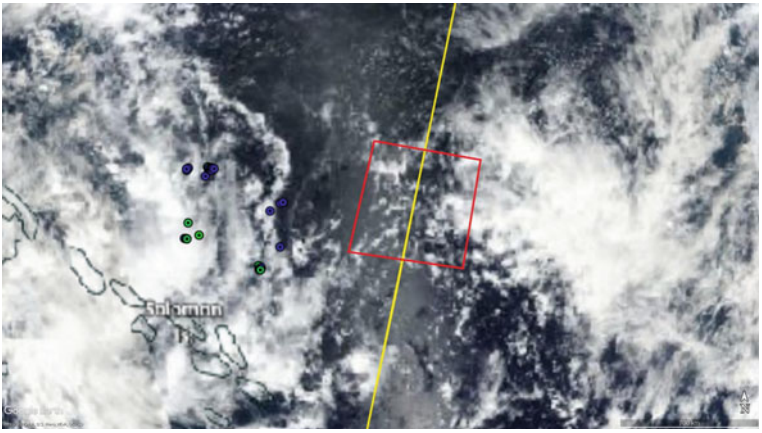

Fig. 8 Maps of lightning discharges with cloud cover from NOAA data. Yellow line is satellite trajectory, red line is the field of view of the central SiPMs (if the detector looks at nadir), blue dots-lightning discharges of negative polarity, green ones-of positive polarity (data of Vaisala GLD360 lightning location network [22]). https://worldview.earthdata.nasa.gov

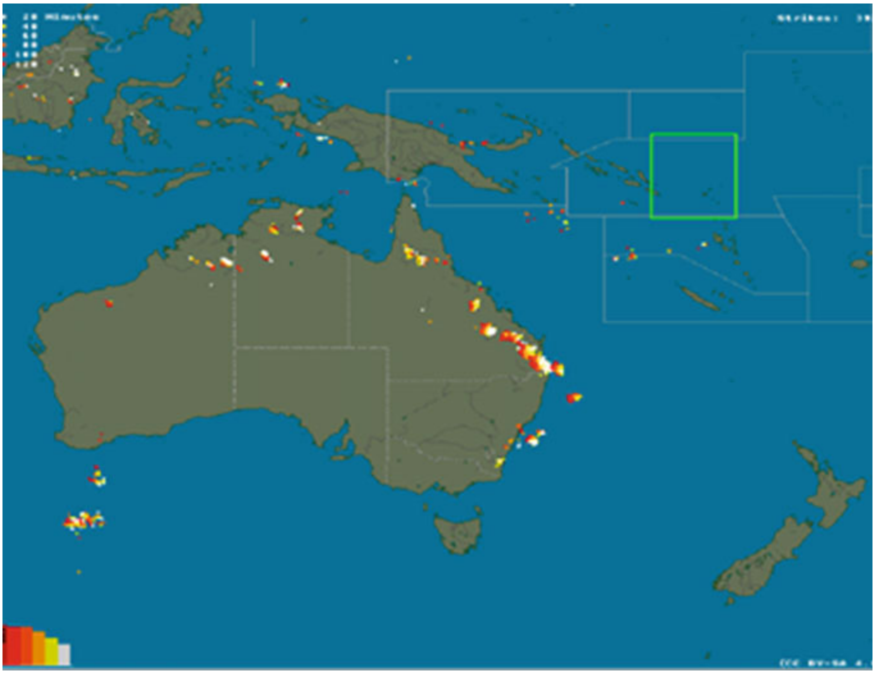

Fig. 9 Maps of lightning discharges from Blitzortung website. https://www.blitzortung.org/ru/live_lightning_maps.php

A series of thunderstorm flashes were detected and analyzed during processing the data acquired during the December 9, 2021 session. The spectral characteristics of the flashes were evaluated. The absence of a significant fraction of red glow is demonstrated. The comparison with the data on the lightning activity in the detection area was carried out. The flashes do not fall into the lightning activity area according to the data of ground-based networks of lightning discharges' location. However, taking into account low efficiency of lightning registration by ground stations and proximity of an extensive area of lightning activity to the detector field of view, the hypothesis about lightning nature of the flashes remains the main one.

This is the first usage of SiPMs in the open space for atmospheric transient emission studies.

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