**Vernov Satellite Data of Transient Atmospheric Events**

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**ABSTRACT**

Data on transient atmospheric events (TAEs) were obtained from the Vernov satellite and are presented in this paper. The data are considered in conjunction with previous data obtained by the Universitetskaya-Tatiana-1 and Universitetskaya-Tatiana-2 satellites. The larger volume of stored scientific data in the Vernov mission and its advanced ultraviolet (UV) and red–infrared (R–IR) radiation detector (DUV) measurements allowed improved TAE-distribution data to be obtained over a wide range of photon numbers. The difference between features of luminous transients and “dim” transients, measured by the Universitetskaya-Tatiana-2 satellite, is confirmed by Vernov’s data. There are also interesting dim UV events with no R–IR radiation. Such events are expected to be deep in the atmosphere at the level of thunderstorm clouds. They might be radiated by electric discharges of less power than lightning; in fact, at the preliminary stage of lightning. The observation of repeating dim TAEs in various time intervals, starting from tens of milliseconds and up to minutes, indicates that thunderstorm electric activity is much more variable than pure lightning strikes.

1. **Introduction**

The Vernov satellite was launched on 8 July 2014 in a polar sun-synchronized orbit with an inclination of 98.4° and a variable height of 640 to 830 km. This satellite became the third scientific–educational satellite from the Moscow State University. The scientific payload Relativistic Electrons (RELEC) on board was to study physical processes responsible for short-term (transient) ultraviolet (UV) and red–infrared (R–IR) radiation from atmospheric transient atmospheric events (TAEs); Panasyuk et al. 2016.

Transient radiation from the atmosphere has attracted attention in previous observations because of its luminous radiation, which was high in the atmosphere (at heights of 40–100 km), correlated with lightning on the cloud level. Those events have been called transient luminous events (TLEs) and have become a subject of many studies. As a phenomenon, they are potentially dangerous for aircraft flying high in the atmosphere. The main features of TLE development have been observed in ground-based and satellite experiments where the measurements have been made by fast cameras directed toward the horizon. Several types of TLEs were found, such as elves, sprites, halos, blue jets, and gigantic blue jets, and their characteristics were measured in temporal and lateral structure (Pasko et al. 2012). Different types of TLE have different sizes and duration and occur at different heights in the atmosphere. Elves occur at heights of 60–100 km with a duration of about 1 ms; sprites occur at heights of 40–100 km with a duration of tens of milliseconds; blue jets occur at heights of 10–40 km and have a duration of hundreds of milliseconds. From satellite observation [data from Imager of Sprites and Upper Atmospheric Lightning (ISUAL) instruments on the Formosa Satellite Mission 2 (FORMOSAT-2); Chang et al. 2010; Hsu et al. 2009; Chen et al. 2008], it was shown that more than 50% of TLEs are elves. Elves have been interpreted as the result of the interaction of a lightning electromagnetic pulse (EMP) with the ionosphere (mainly with the D-layer; Kuo et al. 2007). The short duration of elves (milliseconds) corresponds to
the duration of a lightning strike and the time it takes for an EMP to propagate through the D-layer of the ionosphere. An EMP accelerates ionosphere electrons to energies above an atmospheric molecules’ excitation level and ionization energy. The excitation lines of nitrogen molecules, the species most present in the atmosphere, are in the UV (wavelength 320–420 nm) and R–IR (600–1000 nm) and have been calculated by many authors; see, for example, Fig. 3 in Milikh et al. (1998). The spectrum of TLE radiation presented in that study was for heights in the atmosphere of about 100 km, where both UV and R–IR excited lines occur. Lower in the atmosphere, the intensity of R–IR radiation is suppressed by alternative nonradiative de-excitation. As a result, the color of the TLE depends on atmospheric height: the higher in the atmosphere, the more reddish is the TLE. On the other hand, lightning—initiation of TLEs—does not radiate molecular excitation because atmosphere molecules are dissociated because of the very high lightning temperature. The lightning spectrum was measured by Orville and Henderson (1984) in the range of wavelength 375–888 nm. Emission from the 390-nm nitrogen molecular UV line (the nearest to the visible band) is absent; while R–IR lines are brighter than in the TLE spectrum because of atomic excitation lines. The 777-nm line was chosen as a characteristic feature of lightning for the space Lightning Imaging Sensor (LIS; Christian et al. 2003) developed for monitoring lightning in the atmosphere.

Considering the relative abundance of UV radiation in the TLE spectrum, the determination of TLE events by the intensity of lines in the near-UV band (320–400 nm) was chosen for experiments onboard Moscow State University satellites. Experimental distributions of the ratio R–IR to UV photon numbers showed (Garipov et al. 2013) that most of the events have ratios equal to 3, as expected for TLE events. The “tail” of the distribution of larger ratios, observed in Garipov et al. (2013), has been explained by an addition of lightning discharges to measured TLEs. The high sensitivity of photomultiplier tubes (PMTs) to the UV has preferentially made possible the use of TAEs with low UV intensity for comparisons with lightning. Those “dim” TAEs might be of different origin than TLEs, and in the analysis of experimental data in the present paper, we refer to TLE events as the “luminous” part of all TAEs. Properties of TAEs, including the ratio of R–IR to UV intensity, were measured by the Detector of UV and R–IR radiation (DUV) on board the Vernov satellite. The general description of the DUV with improvements made for the Vernov satellite is presented below. DUV electronics were described in Garipov et al. (2006, 2013) and Sadovnichy et al. (2007).

The DUV contains two Hamamatsu R1463 PMTs with multi-alkali cathodes, covered by filters (Fig. 1). In the UV part of the detector, the Ultraviolet Filter Series-2 (UFS-2) filter is used. This filter is transparent to wavelengths of $\lambda = 240–420$ nm at a 50% transparency level. The quantum efficiency of PMT cathodes in the UV range is 20%, but in the R–IR, the efficiency rapidly decreases to 2% at $\lambda = 700$ nm. The field of view of both detectors is restricted by a collimator, which consists of 80 holes of a 0.8-mm-diameter black material of 2.2-mm thickness. The efficient area of the PMT cathode, which is open for detecting photons, is 0.4 cm$^2$ for a 0° angle to the detector optical axis and decreases to 0 cm$^2$ for a 20° angle. Overall, the geometry factor of every component of the DUV in Vernov is 0.024 cm$^2$ sr. In the Tatiana-2 satellite, the R–IR part of DUV has a geometry factor that is 2 times less.

In TAE observations from a satellite, it is important to take into account the strong absorption of UV by the ozone layer at wavelengths $<320$ nm. For TAEs below the ozone layer, radiation from these UV wavelengths does not reach the detector, while the radiation at wavelengths $>320$ nm goes through the atmosphere with a high >0.7 transparency.

The analog PMT anode signal, collected over an integration time RC $= 30 \mu$m, is digitally converted to a value at every $t_e = 0.5$ ms time sample. The digital data from every PMT are recorded in an operational ring memory. The duration of the waveform for TAE analysis is 128 ms. Information on every waveform was sent to the satellite’s main memory; from there, it was transmitted to the mission control center. The recorded event universal time (UT) was used as the event address. The event frequency was limited by the data transmittance techniques to the mission control center. In the first Tatiana satellite, it was possible to transmit data on TAEs only once per $T = 90$ min (once per satellite orbit). In the second satellite, $T$ was decreased to 1 min, and for the Vernov satellite, $T = 4.5$ s. Trigger conditions were thus chosen to fit these limitations. The trigger...
command was set for every period \( T \), as the event with the largest signal in time sample \( t_s \). Thus, the trigger command was regular over every period \( T \).

The main feature of data acquisition was the use of an automatic PMT gain control system (GCS). The GCS establishes feedback between the UV intensity measurement process by the analog-to-digital converter (ADC) and the dedicated digital-to-analog converter (DAC), which controls the voltage on the PMTs. When ADC code \( N \) increases (decreases) over a comparatively long time of \( t_s = 0.5 \text{s} \) (relaxation time of feedback process), the code \( M \) decreases (increases) by one step, and the PMT voltage follows the \( M \). This feedback process occurs up to the moment when \( N \) becomes equal to a given constant \( N_c \) (=36 in the Vernov case), corresponding to the background UV intensity. The \( M \) for a fixed \( N \) is a measure of the UV intensity; and in Vernov’s DUV, the fact that a UV background intensity measurement is made every 4.5 s, that is, for every 40 km of the atmosphere, is an important asset. The relaxation time of GCS \( (t_s = 0.5 \text{s}) \) is quite long in comparison with the waveform duration of 0.128 s, so the feedback process only slightly changes the \( M \) value in measurements of TAE time-varying profiles.

The TAE signals, selected by the trigger command, were above the background level and were measured as the difference between the TAE signal and the background origin trigger rate is as follows: In a period of 4.5 s, there are many factors that lead to fluctuating background photon number—it is the result of quantum efficiency of PMT cathode \( (\phi) \), which controls the voltage on the PMTs. When ADC code \( N \) increases (decreases) over a comparatively long time of \( t_s = 0.5 \text{s} \) (relaxation time of feedback process), the code \( M \) decreases (increases) by one step, and the PMT voltage follows the \( M \). This feedback process occurs up to the moment when \( N \) becomes equal to a given constant \( N_c \) (=36 in the Vernov case), corresponding to the background UV intensity. The \( M \) for a fixed \( N \) is a measure of the UV intensity; and in Vernov’s DUV, the fact that a UV background intensity measurement is made every 4.5 s, that is, for every 40 km of the atmosphere, is an important asset. The relaxation time of GCS \( (t_s = 0.5 \text{s}) \) is quite long in comparison with the waveform duration of 0.128 s, so the feedback process only slightly changes the \( M \) value in measurements of TAE time-varying profiles.

The above-mentioned trigger command does not always result in a selected TAE. The largest signal amplitude in one trace is between a maximum value \( N \) (4096 for 12-bit ADC used in Vernov) and the \( N_c \) value. The range of the measured TAE full photon numbers is much wider because of the variable background UV intensity (variable \( M \) value) and the variable \( N \) value in the time interval of one TAE.

The value of \( N \) in itself does not represent the fluctuating background photon number—it is the result of many factors that lead to \( N \) fluctuations. An estimate for the background origin trigger rate is as follows: In a period of 4.5 s, there are \( \sim 10^5 \) time samples of \( t_s = 0.5 \text{ms} \), and all those time sample measurements may cause a trigger command. If the distribution of background photon numbers in the field of view (FOV) of the detector is normal, then the trigger command could be caused by a signal larger than 5 standard deviations of average. The estimate of such a signal in \( N \) values shows that the statistical origin of triggers is prevalent for \( N \) values of less than or equal to 60. TAE trigger rate is variable over Earth’s atmosphere: in active thunderstorm regions, TAEs are the main source of all triggers, but in other regions, the background rate prevails.

In short-time waveform intervals (128 ms), \( M \) is constant, and the UV intensity is given by \( N \) in every time sample. In this approach, the temporal profile of both channels of the DUV was recorded by the TAE trigger, elaborated on by the UV channel. The quantities \( N \) and \( M \) determine the number of photons in one time sample:

\[
n_{ph}(N, M) = \frac{NK_jC_t}{G(M)\tau p_j \times 1.6 \times 10^{-19}},
\]

where the capacity of the PMT anode is \( C = 10 \text{pF} \), \( \tau = RC = 30 \mu\text{s} \) is the integration time of the anode circuit, \( 1.6 \times 10^{-19} \) is the electron charge in coulombs, \( p_j \) is the quantum efficiency of PMT cathode \( (j \text{ is the channel index}) \), \( K_j \) is the unit of potential in one ADC sample, and \( G(M) = 10^6(M/179)^{3/2} \) is the PMT gain as a function of \( M \), approximating the results of measurements before the flight.

The emission intensity in the atmosphere is

\[
I(N, M) = \frac{n_{ph}(N, M)}{\omega S},
\]

where \( \omega S = 0.4 \times 0.06 = 0.024 \text{cm}^2 \text{sr} \) is the aperture of every DUV channel.

Taking into account Eqs. (1) and (2), the expression for UV emission intensity can be written as

\[
I_{UV}(N, M) = N_{UV} \times 4.6 \times 10^{24}/M^{3.3},
\]
and the expression for R–IR emission intensity can be written as

\[ I_{R}(N, M) = N_{R} \times 4.6 \times 10^{25}/M^{0.3}. \tag{4} \]

Those formulas are valid from \( M = 179 \) on moonless nights when gain is close to \( 10^{6} \), \( N = 36 \), and intensity \( I_{UV} = 3 \times 10^{7} \) photons (ph) cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) to \( M = 98 \) on a full moon night—\( I_{UV} = 2 \times 10^{9} \) ph cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\). On the dayside of Earth, \( M = 20 \) and \( I_{UV} = 3 \times 10^{15} \) ph cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\); with such a low daytime gain, the PMTs are effectively switched off.

3. Results of intensity measurements of background UV radiation in the atmosphere

The full DUV operational time of the Vernov mission on the night side of Earth was 166.5 h from 8 July to 5 December 2014. The distribution of operational time over Earth in minutes is presented in the upper panel of Fig. 3; the distribution of time of measurements per day during the period of observations is presented in the bottom panel of Fig. 3. The DUV (together with other RELEC detectors) was switched off while crossing the South Atlantic anomaly. The
operational time for the tropical parts of orbits near Indonesia was longer than for other orbits.

During the night side of the orbit, the UV intensity and UT were measured every 4.5 s. At every point, the UV intensity was calculated by Eq. (3) for $M$ and $N$ measurements. The DUV output data along the orbit can be presented by two curves: 1) the track of the satellite nadir points in Earth’s atmosphere and 2) the UV intensity at every point. A typical orbit is presented in Fig. 4 for a moonless night. This is an example of a regular UV intensity level without any special sources in the DUV’s FOV. The results from Vernov are in agreement with the results of Tatiana-2, showing several districts with the lowest UV intensity: 1) deserts like the Sahara, 2) parts of the Pacific Ocean, and 3) parts of Siberia.

The examples of UV intensity increasing over large cities and the auroral oval in polar regions are represented in Fig. 5 and Fig. 6, respectively.

The general increase in UV intensity was observed over all regions of the atmosphere on moonlit nights. On a full moon night, it was up to $2 \times 10^9$ ph cm$^{-2}$ s$^{-1}$ sr$^{-1}$ over cloudless areas and even higher—$4 \times 10^9$ ph cm$^{-2}$ s$^{-1}$ sr$^{-1}$—over

![FIG. 4. (right) An example of a UV intensity time profile along (left) the orbit, which was measured on a moonless night. The intensity increases along the left and right sides of the time–latitude profile are caused by the satellite going from the night side to the day side. This means that the satellite flies from south to north.](image1)

![FIG. 5. The UV intensity along the orbit crossing Japan [particularly Tokyo (35°N)]. Here and in the other figures, the satellite flies from south to north.](image2)
cloudy areas. The highest UV intensities were measured in the terminator region and were on the order of $10^{10} - 10^{12}$ ph cm$^{-2}$ s$^{-1}$ sr$^{-1}$.

4. Results of TAE measurements

a. Observed types of transient events

The analysis of TAEs started with the selection of real transients among events, triggered as a statistical fluctuation of the DUV signal. The trigger conditions were as follows: The largest amplitude measured in a time sample of 0.5 ms in a period of $T = 4.5$ s for a fixed $M$ value was selected. This could occur by a deviation of the value of the number of photoelectrons in ADC counts $N_{ADC}$ from the average $N_c$. The standard deviation ($\sigma$) from the average was measured experimentally for the background UV radiation. The $\sigma$ value was estimated from the distribution of the $N$ value in 256 samples of every waveform (Fig. 2). Additional conditions were introduced to select real TAEs in the offline analysis: the amplitudes should be above some thresholds in two consecutive time samples. The threshold in one time sample should be above $5\sigma$, and in the next sample, it should be above $3\sigma$.

With these additional selection criteria, ~8500 TAEs were collected from ~15,000 background events over the night side of Earth. The temporal profiles of the selected transient events were different, and in the present TAE analysis were divided into three categories (Fig. 7).

In the first “short” type, the duration of the transient event is 1–5 ms, and the amplitudes were beyond statistical fluctuations for several consecutive time samples of 0.5 ms. In the second short type, the short transients were repeated several times in one waveform. In the third “long” type, the duration of the transient was of tens of milliseconds, sometimes filling the full waveform at 128 ms. The temporal profile of this transient type is structured, and short pulses of 1–5 ms are included in the longer transient. For most of the transients selected using the UV profile, the temporal structure in the UV band was repeated in the R–IR band. The ratio of the R–IR intensity to the UV intensity in TAEs is one of the TAE analysis points (see section 4e). An interesting feature of the selected transients is that the short-duration TAE (1–5 ms, types 1 and 2 in Fig. 7) is the dominant type (62% of all TAEs).

b. The TAE distribution on photon number

The experimental data on the TAE photon number from the DUV outputs could be presented as the full number of photons emitted in the atmosphere for the time of a waveform of 128 ms. In all the TAE models generation, the emitted photons are expected to be isotropic. Therefore, the full number of photons, generated in the atmosphere at distance $R$ from the satellite detector, is proportional to the photon number, registered in the detector FOV: the sum of photons in the waveform samples is $\sum q_i(N, M)$ over detector area $S$. If distance $R$ is much more than the TAE size, the full number of photons $Q_{\gamma}$ in a TAE is...
In some cases, the size of the TAE could be comparable to the distance $R$. Equation (5) should be corrected by taking into account only the part of the TAE that is observed in the FOV of the DUV. In the first approximation, when only the transient “brightness” in the atmosphere is of interest, the full number of photons was estimated as given by Eq. (5). The same procedure was followed in the estimation of the TAE photon number in the analysis of the Tatiana-2 data. The comparison of the Vernov results with the Tatiana-2 results helped us understand the role of the DUV trigger, particularly, the role of parameter $T$.

Vernov’s data on the TAE distribution for short (<5 ms in duration) and long (>5 ms) events over the number of photons in the atmosphere $Q_a$ are represented in Fig. 8. Evidently, the longer events contain more photons than short ones. By definition, events with a large photon number are luminous (TLE). Among the short events, there are the lowest-photon-number events with $Q_a < 10^{21}$ (“dim”) to compare with luminous events of $Q_a > 10^{23}$. The difference between the dim events and luminous events is not quite determined; it is rather the difference in their rate that is. This difference was underlined in the Vernov experiment in which the parameter $T = 4.5$ s for triggering was introduced. The comparison of Vernov’s TAE rate with Tatiana-2’s showed an increase of about an order of magnitude in the Vernov case. The categorization of all TAEs into short and long indicates an important feature of the TAE phenomenology: the transients with longer duration are luminous ($Q_a > 10^{23}$). In our case, they are a part of a more general event type called a TAE.

c. TAE distribution over Earth coordinates

The Vernov geographical distribution of TAEs demonstrates the same tendency that was measured in the Tatiana-2 mission: most of the transient events are concentrated above continents near equatorial latitudes, but some events are observed above oceans and at higher latitudes (Fig. 9). It is necessary to mention that the Vernov satellite has a sun-synchronized orbit, which means that its geographical position repeats periodically. This leads to overlapping of the events on the map, which were measured at different times. This fact should be taken into account when analyzing Fig. 9.

A joint analysis of transient atmospheric events measured by Vernov with World Wide Lightning Location Network (WWLLN; http://wwlln.net) data was made. This analysis showed that nearly 80% of flashes
occur in thunderstorm regions (there is lightning within a 1000-km radius around the flash location during a 1-h period).

The transient events, measured in high latitudes above active thunderstorm regions (presumably not associated with lightning), were separated from all TAEs, and their features are discussed in Morozenko et al. (2016).

d. Observation of transient series

In the Tatiana-2 experiment, the phenomenon of the “TAE series” was observed: consecutive transients followed one another with the time between the triggers of $T = 60$ s. The events with three or more consecutive TAE were called a “series” as the event probability of random consequent TAEs is much lower than experimental results (Sadovnichy et al. 2011; Vedenkin et al. 2011; Garipov et al. 2013). In the Vernov experiment, the same approach was used for the search of series occurrences and gave similar results but with a much shorter time interval of $T = 4.5$ s between TAEs. Examples of the TAEs in a series, observed in the Vernov experiment, are represented in Fig. 10. The geographical distribution of the transient series is strongly correlated with the active thunderstorm regions in both experiments. In Fig. 11, the map of Vernov’s series is shown. On the other hand, TAEs that are “not serial” can be seen outside of active thunderstorm regions (Fig. 12).

In an active thunderstorm region, a series of TAEs is expected as events are initiated by independent lightning, which is numerous in such a region. Because of the Vernov data, it became clear that the series are not only long in time (up to 10 min) but are frequent enough for filling a 1-min period with transients, measured every 4.5 s. Similar consequent transients were detected above thunderstorms in the Stimulated Emission of Energetic Particles (SEEP) satellite experiment (Voss et al. 1998). They interpreted the observed series as independent lightning from one large thunderstorm region. In our experiment, a series duration of up to 15 min indicated a

![Figure 8](image_url)  
**Fig. 8.** The Vernov measurements of the TAE photon number distribution. Squares show all events, circles show short events (types 1 and 2; Fig. 7), and triangles show longer events (type 3; Fig. 7).

![Figure 9](image_url)  
**Fig. 9.** Map of TAEs as observed in the Vernov experiment.
large-size thunderstorm region—up to 1000 km and with pulse intervals down to 4.5 s. In some cases, the TAEs follow each other at time intervals down to tens of milliseconds (several photon pulses in one oscilloscope trace of 128 ms; Fig. 7, type 2).

The Vernov experiment produced additional data indicating a more complicated origin of series: members of transient series were observed in cloudless areas where lightning discharges were not expected. The repeating events in one oscilloscope trace of 128 ms were also more frequently observed in the serial transients than in the not-serial transients. More data are required to further understand transient series.

e. Spectral characteristics of TAE

The measurements of TAE spectral characteristics help to interpret their origin. In the previous Tatiana-2 mission (Vedenkin et al. 2011; Garipov et al. 2013), the ratio of the photon number in R–IR band (600–800 nm) to the photon number in UV band (300–400 nm) was discussed. It was compared with a prediction of the ratio value in the TAE emission model because of the excitation of nitrogen molecules in the atmosphere (Milikh et al. 1998). This comparison allows us to estimate the altitude of the transient event, and it was shown that in this assumption, TAE radiation in the atmosphere occurs at relatively high altitudes: $H \approx 60$ km.

The DUV detector measures $N_{ADC}$, and the correct reconstruction of the ratio in terms of photons needs to take into account various factors: the spectrum of photon flux $F(\lambda)$ from the source in the atmosphere, the atmospheric and filter transparency in the range of wavelengths $[\eta(\lambda), \tau(\lambda)]$, and the PMT’s cathode efficiency $p(\lambda)$. In this work, we represent the ratio of signals in two channels of the detector ($P_e = N_{IR, ADC}/N_{UV, ADC}$) distribution and its comparison with expected values in
the assumption of two spectra: sprite spectrum from Milikh et al. (1998) and lightning discharge spectrum from Orville and Henderson (1984). As was mentioned in the introduction, lightning discharges and TLEs have different spectra because lightning radiation is mostly due to excitation of nitrogen atoms (molecules are dissociated in high-temperature lightning discharges).

Figure 13 represents the experimental data obtained by the Tatiana-2 (right panel) and the Vernov (left panel) satellites. To obtain the rough estimation of the photon number ratio, one can simply multiply the $P_e$ value by a factor of 10 (because the average PMT’s cathode efficiency is one order of magnitude lower in the IR band than in the UV band). The $P_e$ ratio was calculated for the two spectra mentioned above, taking into account the actual detector and atmosphere parameters [$\eta(\lambda)$, $\tau(\lambda)$, $p(\lambda)$]. It was found that the $P_e$ ratio for the lightning spectrum from Orville and Henderson (1984) is larger than 1 and for the theoretical spectrum of sprites and the other type of transients, originating in the process of nitrogen molecule radiation in the upper atmosphere, gives a $P_e$ ratio around 0.1. The experimental $P_e$-ratio distribution of selected TAEs in the Vernov and the Tatiana-2 experiments has a maximum at $P_e = 0.1–0.2$. 

![Figure 11](http://journals.ametsoc.org/jamc/article-pdf/56/8/2189/3590993/jamc-d-16-0309_1.pdf)

**FIG. 11.** The map of transient series measured in the Vernov experiment (instruments were switched off in the region of the South Atlantic anomaly).

![Figure 12](http://journals.ametsoc.org/jamc/article-pdf/56/8/2189/3590993/jamc-d-16-0309_1.pdf)

**FIG. 12.** The map of single (not serial) transients observed in the Vernov experiment.
indicating that the majority of measured TAEs are associated with upper-atmospheric events. The tail of the $P_e$ distribution at $P_e > 1$ observed in both the Vernov and Tatiana-2 experiments is very probably lightning-induced radiation. Those events are rare since the selection was made by the UV trigger channel of the events with a large number of UV photons.

As it is shown at the $P_e$ plot for the Vernov experiment, there are numerous events with 0 R-IR photons (Fig. 13, left panel). These UV events occur deep in the atmosphere because the fraction of the red signal increases with altitude. The number of such UV flashes is near 10% of all those measured by the Vernov satellite. These flashes are of great interest because they may represent the part of transient events from low altitudes [blue jets or blue starters, which cannot be the direct consequence of cloud-to-ground lightning (Wescott et al. 1998) or intracloud discharging, which itself develops without leading to a lightning discharge]. An additional analysis of these “pure” UV flashes was done to determine their relation to lightning with the main attention being paid to the dim ones.

To search such events (dim UV flashes in a thunderstorm region but without lightning) the following procedure was applied:

1) The UV flashes (no signal $>3\sigma$ above background in the IR channel) were selected from the Vernov satellite database.
2) Comparison with WWLLN network was done for two time scales (1 h and 10 s) to select events in the region with thunderstorm activity but without lightning during the trigger command period.
3) Comparison with the Vaisala, Inc., GLD360 network was performed to confirm absence of lightning for the selected UV flashes.

Comparison with WWLLN data shows that about 90% of UV flashes occur in thunderstorm regions (there are lightning discharges measured by WWLLN in the radius of 1000 km around the event during 1 h) with a presence of clouds. The remaining part of the events (outside the thunderstorm region) can be explained by the WWLLN thunderstorm measurement efficiency, which is about 80% (Hutchins and Holzworth 2014), but these were excluded from further analyses. Among these 90% of thunderstorm events, the flashes that do not have a corresponding lightning during $\pm 4.5$ s (Vernov’s trigger command period $T$; see the detector description in section 2) in the field of view of the detector according to WWLLN were separated. These events, which amount to 30%, are considered as candidates for the unusual UV flashes. These flashes were compared with the Vaisala GLD360 lightning location network (Said et al. 2010, 2013) to confirm the absence of lightning. These conditions were met for 20% of the events selected after analyses with WWLLN. Two examples of such typical events are shown in Fig. 14. The main features of these flashes are

1) Absence of a signal in the red channel except background;
2) Long duration (the whole waveform of hundreds of milliseconds) with complicated temporal structure (several peaks of tens of milliseconds duration);
3) Low luminosity (maximum ADC < 300, to compare with bright flashes in Fig. 7);
4) Occurrence in thunderstorm region with presence of clouds but without corresponding lightning measured by two ground-based networks, WWLLN and Vaisala GLD 360.

5. Conclusions

The advanced instrumentation on the Vernov satellite for the observation of TAEs confirms the data on TAEs obtained in the previous Tatiana-2 satellite mission. The more detailed data on the average UV intensity in Earth’s atmosphere and on the TAE distribution allowed us to map the UV background intensity and to map the transient events with a time resolution of 4.5 s (before, it was 60 s). Both of those mappings are important for planning ultra-high energy cosmic ray (UHECRs) experiments via observation of atmosphere fluorescence along the direction of the UHECRs’ primary particles (Adams et al. 2013). The higher time resolution of the Vernov detector helped observe the series of transients in more detail, with concentration in active thunderstorm regions. It was shown that transients may fill a region as large as 1000 km with event time intervals of 4.5 s. In some cases, TAEs followed each other at time intervals down to tens of milliseconds (several photon pulses in one oscilloscope trace of 128 ms). It is difficult to interpret this phenomenon as an effect of multiple independent lightning strokes, and more data on correlated in time electric discharges are needed for its understanding.

At the same time, the distribution of all TAEs on ratio $P_e$ indicates that some of the TAEs are generated deep in the atmosphere (on the level of clouds), and some of the registered transients are lightning occurrences in themselves. The dim TAEs, which are rich in UV, might be discharges in the “pre lightning” stage, which do not always develop to the lightning stage or are low-altitude TLEs (blue jets or blue starters).

More data on dim transients will be collected in the Tracking Ultraviolet Setup (TUS) experiment on board the Lomonosov satellite launched on 28 April 2016. The images of transients will be obtained with the help of the large-aperture telescope that consists of a large mirror concentrator ($2 \text{ m}^2$) and a photodetector with 256 pixels with a 5-km resolution in the atmosphere (Adams et al. 2015).

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