PAPER • OPEN ACCESS

On the vertical and horizontal profiles of the atmospheric electric field during thunderstorms

To cite this article: A Chilingarian *et al* 2022 *J. Phys.: Conf. Ser.* **2398** 012002

On the vertical and horizontal profiles of the atmospheric electric field during thunderstorms

A Chilingarian, G Hovsepyan, T Karapetyan, B Sargsyan and M Zazyan,

Yerevan Physics Institute, Alikhanyan brothers 2, Yerevan, Armenia 0036

Abstract We present the first results of a new experiment on Mt. Aragats for measuring the horizontal profile of atmospheric electric fields during thunderstorms. Networks of advanced particle spectrometers operated on the slopes of Mt. Aragats continuously measure fluxes of charged and neutral particles, periodically registering impulsive enhancements, so-called Thunderstorm Ground Enhancements (TGEs). This gives the possibility to estimate the strength of the electric field in the lower atmosphere. Relativistic Runaway Electron Avalanches (RREAs) are registered by the particle detectors located on the Earth's surface as TGEs sometimes exceeding the fair-weather fluxes up to a hundred times. The strong accelerating electric field can reach 1.7-2.2 kV/cm at altitudes 3-6 km, and extend down to 50-150 m above the Earth's surface. The horizontal extent of the electric field can reach 10 km and more.

1. Introduction

In 1992, Gurevich, Milikh, and Roussel-Dupré showed that when Møller scattering (electron-electron elastic scattering) is included, the runaway electrons described by Wilson [1] will undergo avalanche multiplication, resulting in a large number of relativistic runaway electrons for each seed electron (with energies ≈100 keV - 2 MeV) injected into the high-field region [2]. This avalanche mechanism is referred now to as the Relativistic Runaway Electron Avalanche (RREA) mechanism [3,4]. The electric field threshold to activate the electron avalanche was estimated in [5] to be in the range $2.83–3.05 \times 10^5$ $V/m \times n$, where n is the density of air with respect to that at sea level. J.Dwyer [6] investigated the avalanche threshold in detail and found the electric field threshold to be

$$Eth = 2.84 \times 10^5\ V/m \times n,$$

in agreement with the value $2.83 \times 10^5\ V/m \times n$ by Babich [7]. This field threshold field is slightly larger than the breakeven field, which corresponds to the minimum value of the ionization energy losses. If the runaway electrons traveled exactly along the electric field lines, then this would be the threshold for runaway electrons propagation and avalanche multiplication [8]. However, elastic scattering of the electrons with atomic nuclei (Coulomb scattering) and the atomic electrons (Møller scattering) causes deviations in the electron trajectories. In addition, secondary electrons from Møller scattering are usually not created along the field line. As a result, about 20-30 % larger electric fields are required in order for the electrons to run away and the avalanche to multiply. Thus, we adopt the value of *1.8 – 2.2 kV/cm* for the electron accelerating electric field in the thunderous atmosphere at altitudes of 3-6 km.

Thus, if we observe a TGE at Aragats the strength and extension of the atmospheric field cannot be lower than the described above threshold value. In [9] we present several versions of strength and extension of the electric field obtained by CORSIKA simulations of the development of the RRE avalanches at different depths in the atmosphere and for various physically justified strengths of the intracloud electric field (see [10] for detail). CORSIKA code tracks the development of the RREA and calculates the number of electrons and gamma rays in RREA at different stages of avalanche development in the strong electric field; after leaving it particles are tracked for additional 200 m.

2. Horizontal profile of the atmospheric electric field

Monitoring of TGEs on the slopes of Mt. Aragats gives clues to understanding the horizontal extension of the atmospheric electric field, which supports RREA development. The size of the particle emitting region in a thundercloud still remains not well researched. Measurements with several dosimeters installed at nuclear power plants in a coastal area of the Japanese sea made it possible to follow the source of the gamma ray flux moving with an ambient wind flow [12]. At the Nor Amberd research station, located on slopes of the Mt. Aragats at a height of 2000 m, the size of the particle emitting region was estimated using the muon stopping effect [13,14]. Both studies concluded that the particle emitting regions are within ≈1 km. However, in the recent radar-based observations along the coast of the Japanese sea, a strong radar echo indicates that the vertical and horizontal extent of a strong electric field was larger than 2 km [15]. In another observation of the gamma glow in Japan the flux enhancements were initiated and terminated exactly at the same time at a distance of 1.35 km [16]. Thus, the previously estimated values of particle emitting region size within 1 km seem to be highly underestimated. Using a network of STAND1 particle detectors (see details of the network in Fig 2f, [17]) we measure 50 ms and 1s time series of count rates of identical detectors during large enhancements of the particle intensity. The scatter plots demonstrate that Near-Surface Electric Field (NSEF) is rather uniform and stable during TGE on the highland where Aragats station is located. The correlation coefficients between count rates of 3 upper scintillators of 3 identical STAND1 detectors are equivalently large for nearby detectors located at 100 m distance, and remotely located at 300 m distance (Figs 1a and 1c). No delay in correlation is noticed as we can see in Figs. 1b and 1d.

To get insight into the atmospheric field at larger distances we installed networks of NaI spectrometers and electric field sensors of the EFM-100 type on the slopes of Mt. Aragats: five units on Aragats (3200 m), one in Burakan (1700 m), and two in Nor Amberd station (2000 m). Electric mills and lightning locators are installed on Aragats (5 units) and in Nor Amberd (2 units).

During a large storm on the first of May 2022, NSEF disturbances occurred both on Aragats and in Nor Amberd, reflecting the huge sizes of the storm. Storm starts in Nor Amberd and Aragats around 12:00 UT (start of disturbances of the NSEF) and finished at ≈14:30 UT.

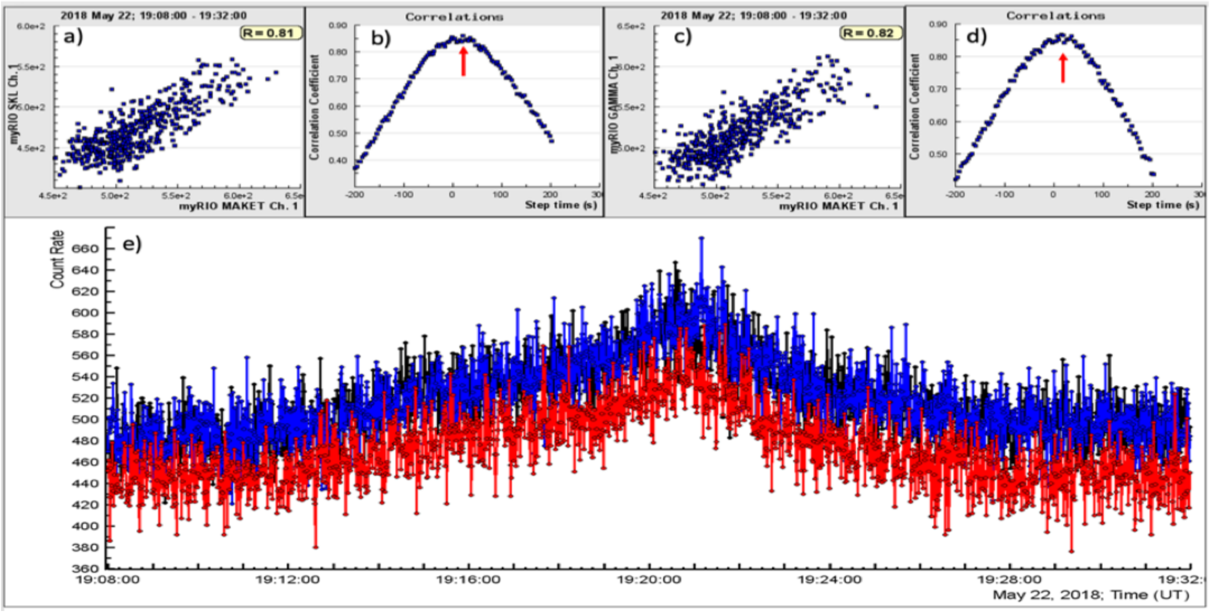

Figure 1. a) and b) scatter plot and delayed correlations plot of count rates of STAND1 detector's upper 1-cm thick scintillators (MAKET and SKL detectors); c) and d) the same for the MAKET and GAMMA detectors; e) 1-sec time series of all 3 units of STAND1 network: MAKET (black), GAMMA (blue), and SKL (red).

Correspondent enhancements of particle fluxes measured by NaI detectors were detected on slopes of Mt. Aragats at 12:40-14:00 UT. The storm was approaching Armenia from the south and a maximum lightning flash was far from the stations nearby Armenia's border with Turkey. Nonetheless, disturbances of NSEF were very large even on the periphery of the storm. In Fig. 2 we show 1-minute time series of count rates measured by 5 cm thick and 1 m^2 area plastic scintillators located under a 0.8 mm iron roof on Aragats and in Nor Amberd. Large enhancements of the count rated occurred on Aragats at 13:00 – 13:14 UT and 13:23-13:33 UT, in Nor Amberd at 12:30-13:23 UT. The significances of the largest peaks were 5,7% (9σ) and 6.6% (8.2σ) on Aragats and in Nor Amberd correspondingly. Thus, in spite that the lightning active zone was far from Aragats, the electric field in the clouds above Aragats was above critical value for activating the runaway process and the electron accelerator operates for tens of minutes on both stations.

The NSEF changes during TGE from -23 to 8 kV/m on Aragats, and from -25 to 25 kV/m in Nor Amberd. The TGE occurred on Aragats during the deep negative electric field, and in Nor Amberd during positive NSEF. Thus, in spite of rather different conditions of the NSEF disturbances, and different charge structures in the cloud above, the TGEs in both stations, registered by the same type of detectors share the same time. We checked the TGEs also by other particle detectors, on Aragats with solar neutron telescope [19], NaI spectrometer, 1 and 3 cm thick plastic scintillators, and in Nor Amberd with an array of Geiger counters located outdoors. The observed significances of peaks were compatible with the ones described above.

Another large storm occurred on Aragats on September 6. It was accompanied by numerous lightning flashes on both stations, see Fig. 3a. The pattern of the NSEF disturbances was approximately identical on both stations. The particle flux enhancement started on both stations simultaneously at 15:59 UT, see Fig. 3b. The maximum value of 2 identical particle detectors was achieved in Nor Amberd at 16:01 UT, and on Aragats at 16:07 UT, and 16:08 UT.

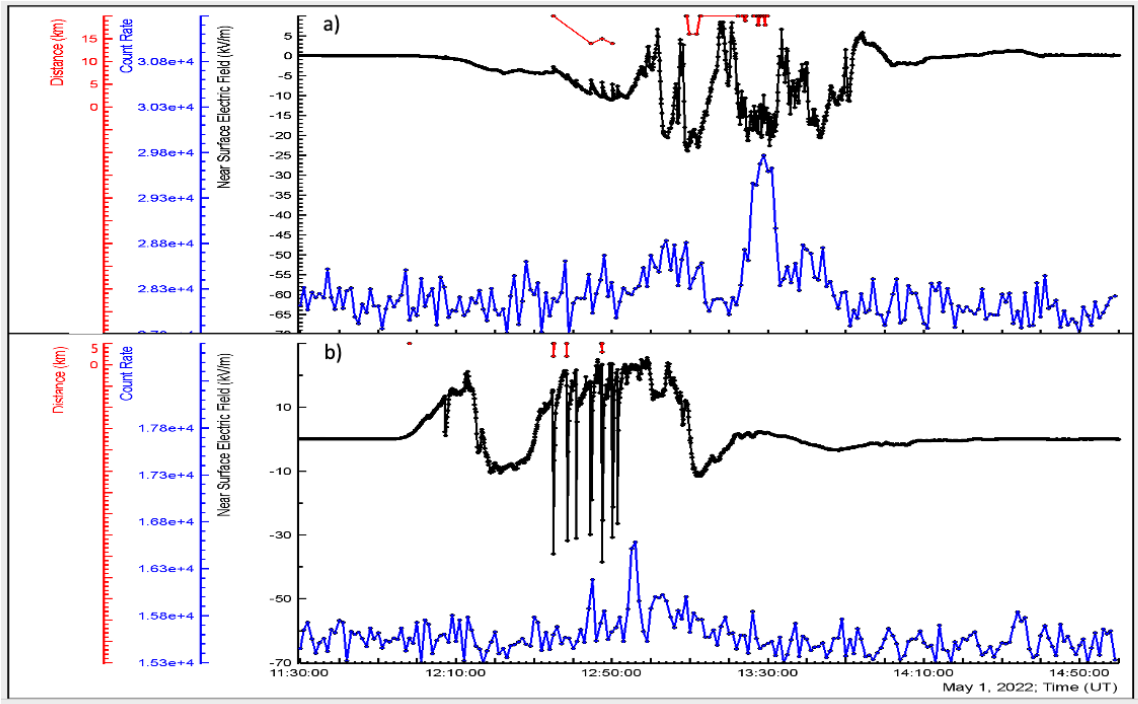

Figure 2. Disturbances of the NSEF (black); 1-minute time series of count rates of 5 cm thick and 1 m^2 area plastic scintillators (blue); and distances to lightning flashes (red) measured on Aragats a) and in Nor Amberd b).

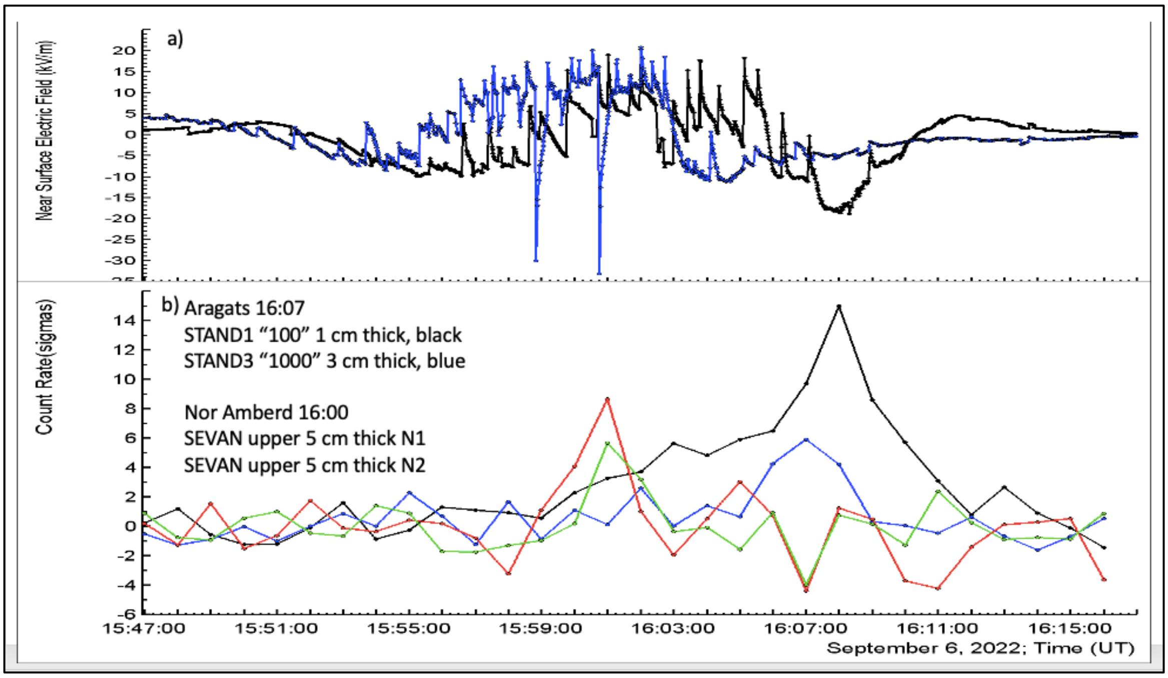

Figure 3. a) Disturbances of the NSEF measured on Aragats (black) and in Nor Amberd (blue); b)1-minute time series of count rates of 1 cm and 3 cm thick (both 1 m^2 area) plastic scintillators on Aragats (black and blue) and 2 identical 5 cm thick and 1 m^2 area plastic scintillators in Nor Amberd (red and green).

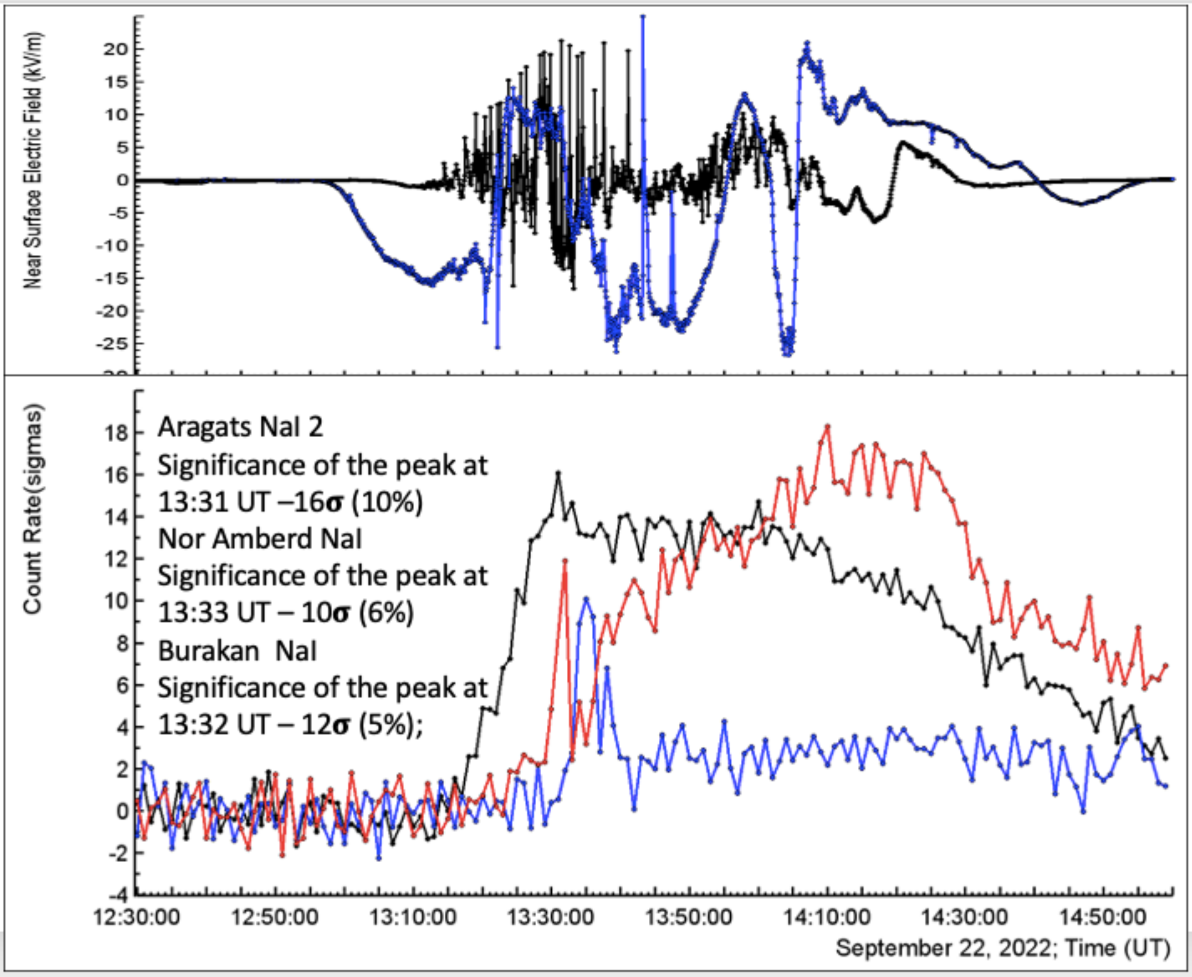

Figure 4. a) Disturbances of the NSEF measured on Aragats (black) and in Nor Amberd (blue); b)1-minute time series of count rates of NaI (Tl) detectors on Aragats (black), in Nor Amberd (blue), and in Burakan (red).

Rather large significances of peaks for all 4 detectors leave no doubt that TGE occurred on both stations located on a horizontal distance of 13 km and a height difference of 1.2 km at the same time. In Fig.4 we present an episode from a very long storm that occurred on September 22, 2022. This time the pattern of NSEF disturbances was different on both stations. On Aragats again multiple lightning flashes were observed, and in Nor Amberd there were a few flashes but the amplitude of NSEF fluctuations was rather large. The TGE occurred when NSEF on both stations was in the positive domain, see Fig 4a. The TGE was measured with NaI(Tl) detectors. At this time a large flux was observed also in Burakan, 3 km far and 200 m lower than Nor Amberd. Close occurrences of flux enhancements in time and very large significances of peaks leave no doubt that this time avalanches covered an even larger area than on September 6 extended by 15 km. In Fig. 5 we present evidence of the TGE occurrence in Nor Amberd. To register spatial extension of individual RRE avalanches (produced by a single free electron entering a strong field region) we measure coincidences in signals (with a window of 800 ns) of 2 detectors located within a 3 m^2 area. During 5 minutes of TGE (from 13:34 UT to 13:39 UT) the count rate abruptly increased from ≈20 to 62 (at 13:36 UT), see Fig. 5.

Thus, the electron-gamma ray avalanches at flux intense minutes covered a 3 m^2 area. However, as we already have shown RREAs coming one after another on a second time scale are covering much more area reaching several square kilometers. Here we register a TGE from one seed electron, avalanche particles are coming within one microsecond. On September 19, 2009, TGE size originated from one seed (all particles registered within 1 microsecond) was estimated by the MAKET array (stopped now) to be several hundred square meters.

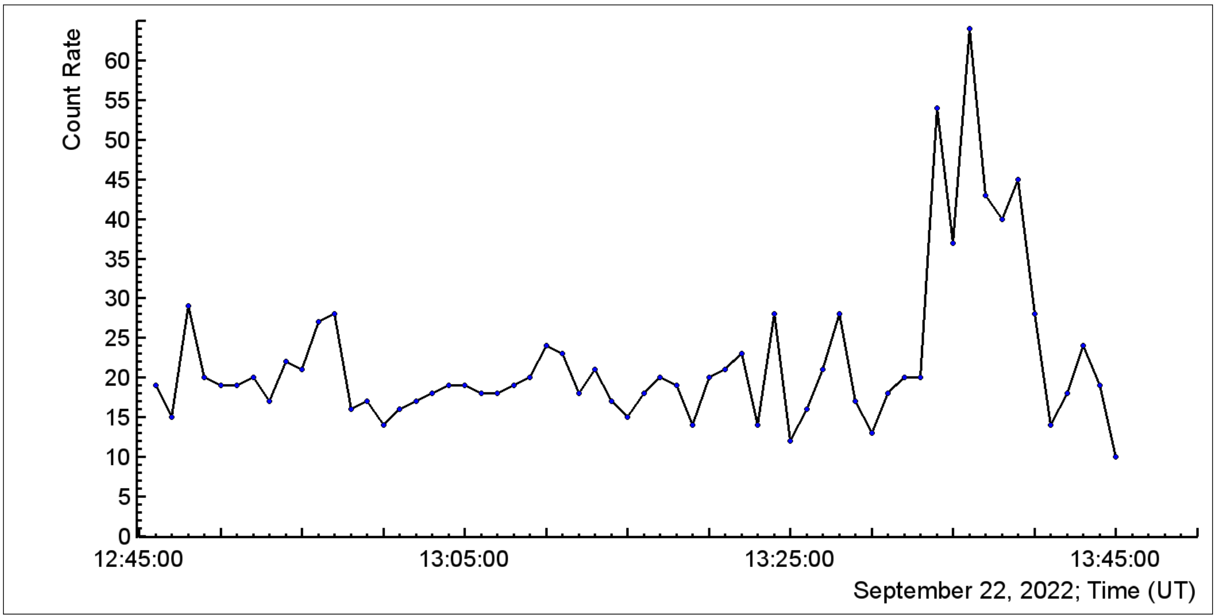

Figure 5.1-minute time series of count rate of coincidence of 2 identical 1 m^2 plastic scintillators and NaI(Tl) detector located in Nor Amberd.

3. Conclusions

Our measurements show that a strong electric field covers huge volumes in the thunderous atmosphere. RREAS are accelerated to large energies by atmospheric electric fields and end up as TGEs, which allocate to the earth's surface sizable doses of radiation. This additional radiation should be introduced to the models of weather forecasting and global change. Remote sensing of electric fields in the lower atmosphere by measuring the fluxes of electrons and gamma rays reveals the large extension of the strong electric field both vertically and horizontally. Remote sensing can be done on the Earth's surface distant from the storm and it does not require balloon launches near the most intense weather. Surface detectors are stable and long-leaving, they are not moved by wind or destroyed by lightning flash like balloons. Several detectors can monitor multiple regions of interest simultaneously. The time resolution is in the order of seconds, and monitoring is performed 24/7, without a chance of missing violent storms. Especially important is the monitoring of the strong electric field just above the ground, which can reach very high values just tens of meters above the Earth's surface. The remote sensing of the atmospheric field can be used along with a field mill climatology, which is usually saturated at high electric fields, to minimize the risk of launching space vehicles during thunderstorms [21].

Acknowledgments: we thank the staff of the Aragats space environmental center for the uninterruptable operation of all particle detectors and field meters. Authors acknowledge the support of the Science Committee of the Republic of Armenia (research project no. 21ag-1c012), in the modernization of the technical infrastructure of high- altitude stations.

References

[1] Wilson C T R 1925 *The acceleration of β-particles in strong electric fields such as those of thunderclouds* (Mathematical Proceedings of the Cambridge Philosophical Society; 22(4):DOI:10.1017/S0305004100003236) p534–538

[2] Gurevich A, Milikh G and Roussel-Dupre R 1992 *Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm* (Physics Letters A 165 (5)) p 463 – 468

[3] Babich L P, Kutsyk I M, Donskoy E N, Kudryavtsev A Yu 1998 (Phys. Lett. A 245) p 460–470

[4] Babich L P et al. 2001 (IEEE Trans. Plasma Sci. 29(3)) p430–438

[5] Roussel-Dupre R, Symbalisty E, Taranenko Y, Yukhimuk V, Atmos J. 1998 (Sol.-Terr. Phys. 60) p 917–940

[6] Dwyer J R 2003 *A fundamental limit on electric fields in air* (Geophys. Res. Lett. 30, 2055).

[7] Babich L P, Donskoy E N, Il'kaev, R I, Kutsyk I M, Roussel-Dupré R A 2004 (Plasma Phys. Rep. 30) p616–624

[8] Dwyer J R, Smith D M, Cummer S A 2012 *High-Energy Atmospheric Physics: Terrestrial Gamma-Ray Flashes and Related Phenomena* (Space Sci Rev 173: DOI 10.1007/s11214-012-9894-0) p133–196

[9] Heck D, Knapp J et al. 1998 *CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers* (Report FZKA 6019 Forschungszentrum Karlsruhe)

[10] Chilingarian A, Hovsepyan G, Svechnikova E, Zazyan M, 2021 *Electrical structure of the thundercloud and operation of the electron accelerator inside it* (Astroparticle Physics 132 102615)

[11] Sato T 2016 *Analytical model for estimating the zenith angle dependence of terrestrial cosmic ray fluxes*, (PLOS ONE 11 e0160390)

[12] Torii T, Sugita T, Kamogawa M., Watanabe Y and Kusunoki K 2011 *Migrating source of energetic radiation generated by thunderstorm activity* (Geophysical Research Letters, 38 24).

[13] Chilingarian A, Hovsepyan G, Karapetyan G, and Zazyan M 2021 *Stopping muon effect and estimation of intracloud electric field* (Astroparticle Physics 124 102505)

[14] Chilingarian A, Bostanjyan N, Karapetyan T 2013 *On the possibility of location of radiation-emitting region in thundercloud* (IOP Publishing Journal of Physics: Conference Series 409 012217 doi:10.1088/1742-6596/409/1/012217)

[15] Wada Y, Enoto T, Kubo M, Nakazawa K, Shinoda T, Yonetoku D et al. 2021 *Meteorological aspects of gamma-ray glows in winter thunderstorms* (Geophysical Research Letters, 48, e2020GL091910. https://doi. org/10.1029/2020GL0919100)

[16] Hisadomi S, Nakazawa K, Wada Y, Tsuji Y, Enoto T, Shinoda T, et al. 2021 *Multiple gamma-ray glows and a downward TGF observed from nearby thunderclouds* (Journal of Geophysical Research: Atmospheres, 126, e2021JD034543. https://doi. org/10.1029/2021JD034543)

[17] Chilingarian A, Hovsepyan G, Karapetyan T et al. 2022 *Multi-messenger observations of thunderstorm-related bursts of cosmic rays*, (*JINST* 17 P07022).

[18] https://www.boltek.com/manual-pci.pdf

[19] Chilingarian A, Hovsepyan G, Karapetyan T et al. 2022 *Measurements of energy spectra of relativistic electrons and gamma-rays avalanches developed in the thunderous atmosphere with Aragats Solar Neutron Telescope* (Journal of Instrumentation, 17 P03002).

[20] Chilingarian A., Hovsepyan G., and Hovhannisyan A., *2011 Particle bursts from thunderclouds: Natural particle accelerators above our heads, (*Physical review D 83, 062001).

[21] Gardner S.C., *Using a field mill climatology to assess all lightning launch commit criteria*, AFIT-ENV-MS-20-M-204, 2020.