# How can we simulate ionizing radiation at aviation altitudes from TGFs?

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**Abstract.** So-called thunderclouds, which are large dark clouds that are able to generate thunder and lightning, can act as natural particle accelerators, producing complex high-energy phenomena such as terrestrial gamma-ray flashes (TGFs) and gamma-ray glows. These events are often described through the mechanism of relativistic runaway electron avalanches (RREAs), cascades of high-energy electrons accelerated by atmospheric electric fields. Since the energies of the RREAs are up to several tens of MeV, they can also trigger nuclear reactions with atoms of the air and in the soil while entering the ground. Although these phenomena are intriguing, their lack of precise measurement and still not completely understood origins pose a significant challenge for assessing their impact on aviation safety. This paper introduces the project Research Centre of Cosmic Rays and Radiation Events in Atmosphere (CRREAT), aimed at providing measurements of TGFs, thunderstorm ground enhancements (TGEs), and other ionizing radiation phenomena during thunderstorms, as well as at aviation altitudes, stratosphere, and low Earth orbits (LEO). The paper argues that without accurate data on the origins and physical characteristics of TGEs and TGFs, it is impossible to reliably simulate their impact on aircraft crews and passengers. The paper also mentions how the general-purpose 3D Monte Carlo (MC) code PHITS can be used for future simulations and comparisons with measurements related to ionizing radiation phenomena in the atmosphere.

## 1 Introduction

Various phenomena contribute to ionizing radiation in the atmosphere, and on Earth's surface. These include solar energetic particles (SEPs), such as protons, electrons, and a limited number of neutrons. These neutrons are generated during solar neutron events (SNEs), during which accelerated protons and heavy ions collide and produce neutrons. There are also galactic cosmic rays (GCRs), mainly originating from supernova events outside our solar system [1]. When GCRs and SEPs interact with Earth's atmosphere, they create secondary particles like neutrons, protons, pions, muons, etc. Intense solar gamma-ray events (SGEs) also occur during solar flares. Near Earth, particles are trapped in the two

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Van Allen Belts, which are zones of energetic charged particles mostly originating from the solar wind and held in place by Earth's magnetosphere.

Both empirical measurements and theoretical studies indicate that thunderstorms can act as natural particle accelerators [1,2]. During the thunderstorms, electrons which are traveling at speeds close to the speed of light collide with atmospheric nuclei, releasing energy in the form of X-rays (bremsstrahlung) and gamma rays. These storms can generate terrestrial gamma-ray flashes (TGFs), which are bursts of gamma rays with energies ranging from below 10 keV to about 40 MeV. These bursts last for microseconds and occur in sequences separated by hundreds of microseconds, with the entire event lasting up to milliseconds. The gamma rays can further induce photonuclear reactions [1,2].

Relativistic runaway electron avalanches (RREAs) are other phenomena that can occur [3-14]. These are large populations of high-energy electrons formed by avalanche growth driven by electric fields in Earth's atmosphere. The electric field might terminate due to a lightning discharge, which usually occurs when the voltage and electron energies are highest. Therefore, TGFs are typically measured within a few milliseconds of a lightning event [15-20]. Besides TGFs, long-lasting radiation events called thunderstorm ground enhancements (TGEs) can also occur, involving increased fluxes of electrons, neutrons, gamma rays, or X-rays [3-14].

The radiation risk for aircraft crews at flight altitudes is usually evaluated by computer codes that consider only the dose from GCRs [21], verified by measurements by various ionizing radiation detectors [22,23]. However, high-energy phenomena during thunderstorms could also significantly contribute to the radiation dose onboard aircraft [1,24,25]. TGFs might have an important effect on aircraft electronics as theoretically studied in [26]. Authors have previously pointed out the necessity of dedicated measurement campaigns addressing the radiative and particle environment of aircraft near or within thunderstorms [8, 27, 28, 29]. To better understand these phenomena, the Nuclear Physics Institute (NPI) of the Czech Academy of Science CAS (NPI), the Institute of Atmospheric Physics of the CAS (IAP), and the Faculty of Electrical Engineering of the Czech Technical University in Prague (CTU) have created the Research Center of Cosmic Rays and Radiation Events in the Atmosphere (CRREAT). The CRREAT team measures both lightning and ionizing radiation during thunderstorms using detectors mounted on cars and on high mountains, and the dose contribution from these high-energy phenomena using various methods, including CR measurements onboard aircraft [23,30,32,33], on-ground tests [32,34], and real measurements onboard unmanned aerial vehicles. The team is also performing long-term monitoring using a hybrid detector onboard commercial aircraft [35].

The project also includes 3D MC simulations of these measurements. The infrastructure built for continuous measurement of CRs and radiation events in the Czech Republic may be used for future research projects requiring measurements with good time resolution on the Earth's surface.

# 2 Measuring thunderstorms with high-speed cameras and radio receivers

## 2.1 Measurement techniques

To accurately capture the various phenomena occurring during thunderstorms, specialized measuring equipment has been installed on mobile units, as illustrated in Figure 1. These vehicles can move to locations with forecasted storm activities, enabling real-time ground measurements at the site of the storm.

### 2.2 Instrumentation and data collection

To collect essential data on lightning activity and its correlation with ionizing radiation events, such as timestamps of lightning events, types of lightning, duration, and geographical location, the cars are equipped with a range of instruments. These include high-speed all-sky cameras, radio receivers, meteorological sensors, and more recently, a UAV (Unmanned Aerial Vehicle) takeoff platform. The UAV platform is used to launch a drone equipped with additional instruments TF-ATMON system [1].


**Figure 1.** Examples of CRREAT's measuring cars equipped with a variety of instruments for capturing essential parameters of lightning activity and its relation to ionizing radiation events. The instrumentation includes high-speed all-sky cameras, radio receivers, meteorological sensors, and ionizing radiation sensors [1].

### 2.3 Observations and findings

Measurements conducted in both the Czech Republic and the Slovak Republic have led us to observe that the median duration of a lightning event exceeds 0.5 seconds [36]. This duration is notably longer than the values reported in existing literature (200–300 ms) [37] and 350 ms [38].

### 2.4 Data Visualization techniques

To enable visual interpretation of the collected data, we have developed specialized visualization techniques that allow for the integrated display of data from various sensors. This makes it possible to video record the lightning in different colors on the video, with displayed graphs of outputs of different instruments respect to time. In Figure 3, a screenshot from a video with graphs of luminosity and data from a very low-frequency (VLF) antenna is shown as an example. This makes it also possible to compare different lightning records with each other, and data from different instruments, so we can reconstruct and characterize the individual phases of the lighting development. Together with measurements of lightning durations, it gives important information for designing future storm-based ionizing radiation observations.

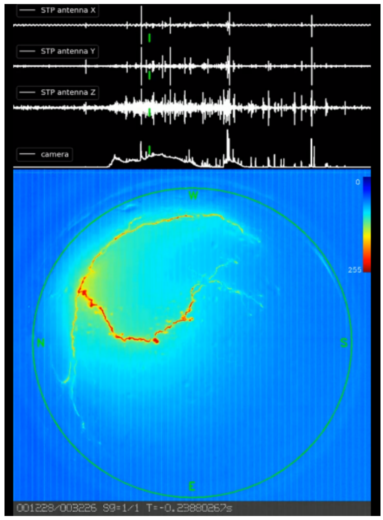


**Figure 2.** Example of a screen shot of a video illustrating the visualization technique of lightning [1].

# 3 Measurements of high-energy photons on high mountains observatories and in forests

## 3.1 The GASTRON network

The CRREAT project has established a network of high-resolution gamma spectrometers at high-altitude observatories across Europe. This network, known as the gamma spectrometry of thunderstorm radiation observatory network (GASTRON), is remotely controlled from Prague and managed by an in-house server. Table 1 lists the locations where GASTRON detectors currently are installed.

In August 2020, a large gamma spectrometer Georadis RT 56 equipped with a 4 × 4 × 16 inch$^3$ NaI(Tl) crystal, photomultiplier tube (PMT) and electronics for data acquisition was installed by the CRREAT project in Lomnický štít in Slovakia to measure ionizing radiation related to thunderstorms [28]. This spectrometer can record the primary spectrum up to 9216 keV, divided in 1024 channels, and the "cosmic" spectrum in 256 channels. In ref. [28] more details about the measuring setup are given. The Lomnický štit in Slovakia is a place of extreme measured electric fields during thunderstorms [39,40]. The observatory is also equipped with the SEVAN detector system [1,3], which consists of three plastic scintillator detectors each coupled with one photomultiplier tube (PMT). The RT 56 gamma spectrometer and the SEVAN detector systems are shown in Figure 3. In Figure 4, an example of an event detected by both RT-56 spectrometer and SEVAN detector on September 12, 2021, at the on Lomnický štit, is shown.

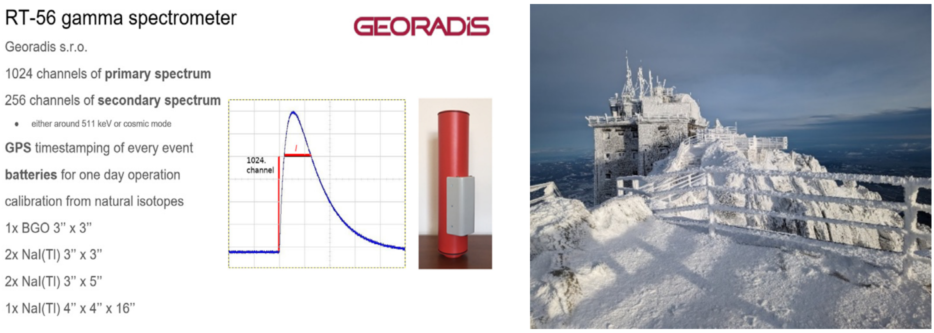


**Figure 3.** The RT 56 Gamma spectrometer and the SEVAN detector system installed Milesovka in Czech Republic to measure ionizing radiation related to thunderstorms [29].

In Figure 4, the observed TGE spectrum during one minute (September 12, 2021) at the peak with the highest flux is shown together with the background spectrum. In the same figure, TGE + background, and a simulation of deposited energies from muons, is shown. The simulation was performed with the general-purpose 3D MC Particle and Heavy Ion Transport code System (PHITS), version 3.24 from 2021 [41], with the built in source terms for GCR and transportation through the atmosphere.

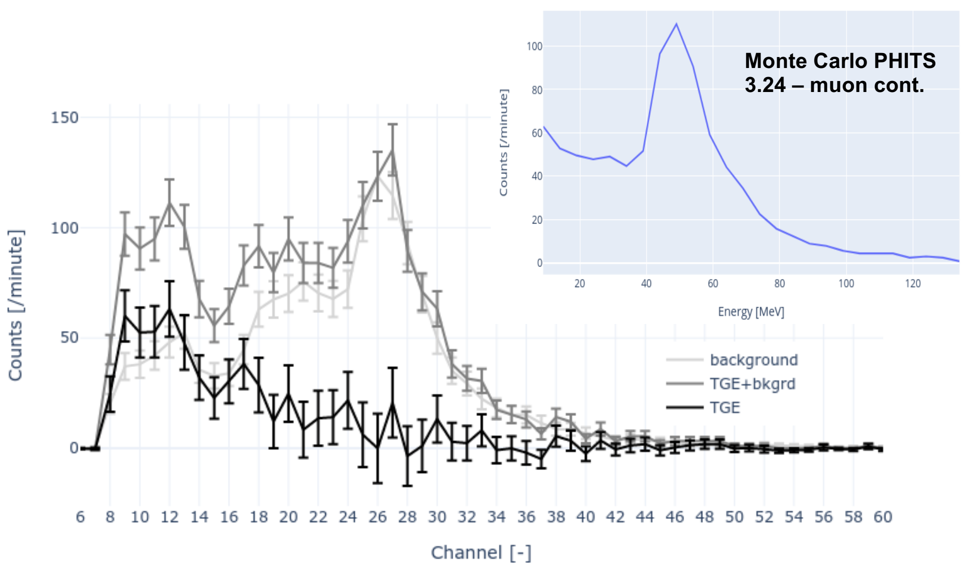


**Figure 4.** Main graph: Cosmic mode of RT-56. Background taken from 19:50-20:00 (light grey), observed spectrum during one minute of the peak with highest flux taken from 20:06:20-20:07:20 (grey), difference between the two (black). Error bars show 1σ errors. Upper-right: MC simulation of muons in RT-56 [1,27]. The dip in the measured spectrum around channel 14, which can be seen in both the TGE and background spectra, is believed to be caused by the detector geometry since the energy deposition of muons is very dependent on geometry of the detector crystal. It might also be due to saturation of the amplifiers. The energy calibration is complex and there is a close to logarithmic dependence of the channel on the energy. The evaluation of the measured spectra is ongoing.

Another component of the GASTRON network is the GEODOS detectors, which are designed for deployment in areas without access to electrical grid power. In Figure 5, an example of the detector in the Šumava National Park is shown. These off-grid detectors expand the reach of the GASTRON network, allowing for more comprehensive data collection in diverse settings, from high-altitude observatories to remote natural reserves like national parks.

**Figure 5.** Example of a GEODOS detector deployed in Šumava National Park, illustrating the adaptability of the GASTRON network to various environmental conditions.

Some events that are potential candidates for TGEs or TGFs were detected by the GEODOS detectors in 2021 [42]. In Figure 6, we present an example of an event from August 15, 2021. It was observed that the first increase of the ionizing radiation flux involved particles with energies exceeding 800 keV. These were detected within a very short time frame of tens of milliseconds. During the entire 15-second measurement interval, there was a noticeable increase in particle flux, primarily in the energy range of approximately 350 to 550 keV, as can be seen in Figure 7. This was followed by a rapid decrease within one minute, possibly indicating of radioactive decay triggered by the activation of surrounding materials. The primary increase in radiation lasted tens of ms, which is quite atypical for both TGE and TGF.

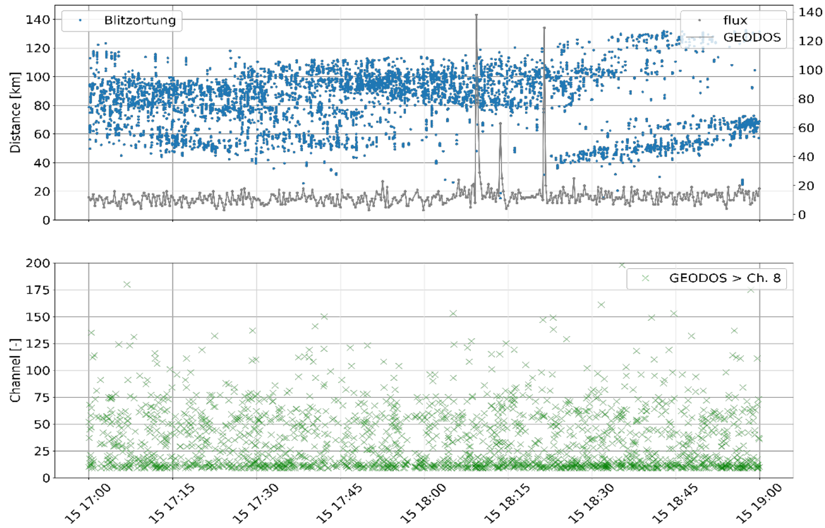


**Figure 6.** A temporal detail of the event from August 15th, 2021, captured by GEODOS at the Poledník tower. The upper image displays the distance (blue) from lightning discharges and the counts of detected ionizing radiation particles (grey). The lower image shows individual detected events at the more energetic channels.

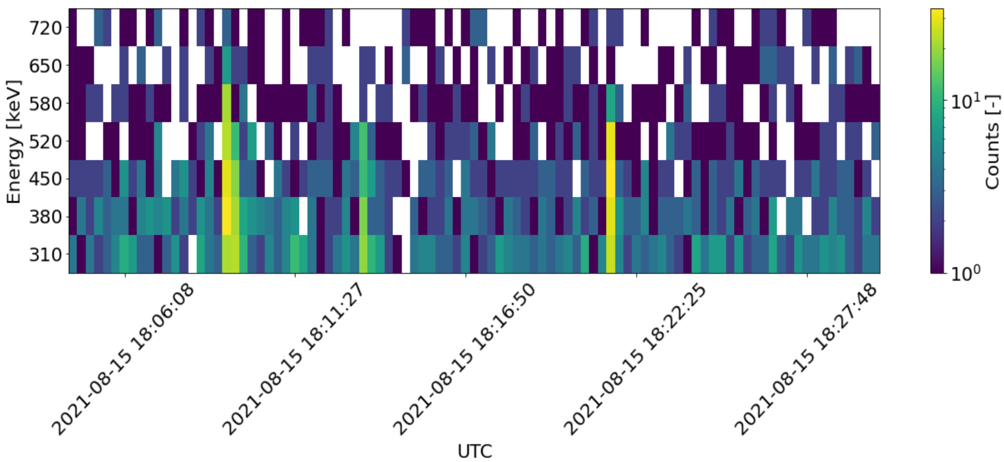


**Figure 7.** Evolution of detected energies over time for the event on August 15th, 2021.

**Table 1.** Locations of the GASTRON detectors.

| Place/observatory | Country | Altitude [m] |
|---|---|---|
| Milešovka, Bohemian Central Mountains | Czech Republic | 837 |
| Poledník, Šumava Mountains | Czech Republic | 1,315 |
| Křešín atmospheric observation mast | Czech Republic | 535 + 225 |
| Musala, Rila | Bulgaria | 2,925 |
| Zugspitze, Wetterstein Mountains | Deutschland | 2,962 |
| Jungfraujoch, Bernese Alps | Switzerland | 3,454 |
| Säntis | Switzerland | 2,502 |
| Lomnický štít, High Tatras | Slovakia | 2,634 |

## 4 Summary

The ionizing radiation environment in Earth's atmosphere is complex and still not fully understood. It is a result of interactions of charged particles of solar and galactic origin with the magnetosphere and the atmosphere of the Earth. The intensities and the composition of the radiation field change with latitude and altitude and with the solar activity. There are also local short contributions of radiation originated from thunderstorms, which can act as particle accelerators. This paper gives an overview of the activities of the CRREAT team, and describes some of the detector systems developed by CRREAT to characterize the radiation field of thunderstorms on ground and at aviation altitudes. It also presents measurements performed with cars equipped with measuring devices to characterize the thunderstorms, including duration of the lightning and the produced ionizing radiation. A new network of high-resolution gamma spectrometers (GASTRON) at high-altitude observatories in Europe is also described. The TGFs and TGEs measured by CRREAT will be used to develop models for the origin of such phenomena. The models will then be used to better understand these phenomena and to estimate the radiation risks of TGFs to airplane crew and passengers flying near thunderstorms. 3D general-purpose MC codes, e.g., PHITS, can be used for future simulations and comparisons with measurements related to ionizing radiation phenomena in the atmosphere and on ground, but without accurate data on the origins and physical characteristics of TGEs and TGFs, it is impossible to reliably simulate their impact on aircraft crews and passengers, so additional measurements at aviation altitudes and on ground are needed.

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## References

[1] Sihver, L., Ploc, O., Turek, K., Kákona, M., Kákona, J., Šlegl, J., Ambrožová, I., Lužová, M., Velychko, O., Sommer, M., Langer, R., Measurements of Ionizing Radiation Generated in Thunderstorms, in the proc. of the 44th IEEE Aerospace Conference (IEEEAC) paper, Big Sky, MT, USA, March 4-10, 2023

[2] Enoto, T., Wada Y., Furuta Y., Nakazawa K., Takayuki Y., Okuda K., Makishima, M., Sato, Y., Nakano, T., Umemoto, D., Tsuchiya, H., Photonuclear reactions triggered by lightning discharge. Nature 551, 481–484 (2017). Doi:10.1038/nature24630

[3] Chilingarian, A., Hovsepyan, G., Arakelyan, K., Chilingaryan, S., Danielyan, V., Avakyan, K., Yeghikyan, A., Reymers, A., and Tserunyan, S. Space environmental viewing and analysis network (SEVAN), Earth Moon Planets, 104, 195–210, https://doi.org/10.1007/s11038-008-9288-1, 2009

[4] Chilingarian, A., Daryan, A., Arakelyan, K., Hovhannisyan, A., Mailyan, B., Melkumyan, L., and Hovsepyan, G. Ground-based observations of thunderstorm correlated fluxes of high-energy electrons, gamma rays, and neutrons. Phys. Rev. D, 82, 043009, https://doi.org/10.1103/PhysRevD.82.043009, 2010

[5] Chilingarian, A., Hovsepyan, G., and Hovhannisyan, A.: Particle bursts from thunderclouds: Natural particle accelerators above our heads. Phys. Rev. D, 83, 062001, https://doi.org/10.1103/PhysRevD.83.062001, 2011

[6] Chilingarian, A., Mailyan, B., and Vanyan, L. Recovering of the energy spectra of electrons and gamma rays coming from the thunderclouds, Atmos. Res., 114–115, 1–16, https://doi.org/10.1016/j.atmosres.2012.05.008, 2012

[7] Chilingarian, A., Chilingaryan, S., and Reymers, A. Atmospheric discharges and particle fluxes, J. Geophys. Res.-Space, 120, 5845–5853, https://doi.org/10.1002/2015JA021259, 2015

[8] Chilingarian, A., Hovsepyan, G., and Kozliner, L. Extensive air showers, lightning, and thunderstorm ground enhancements, Astropart. Phys., 82, 21–35, https://doi.org/10.1016/j.astropartphys.2016.04.006, 2016

[9] Chilingarian, A., Chilingaryan, S., Karapetyan, T., Kozliner, L., Khanikyants, Y. Hovsepyan, G., Pokhsraryan, D., and Soghomonyan, S. On the initiation of lightning in thunderclouds, Sci. Rep., 7, 1371, https://doi.org/10.1038/s41598-017- 01288-0, 2017a

[10] Chilingarian, A., Khanikyants, Y., Mareev, E., Pokhsraryan, D., Rakov, V. A., and Soghomonyan, S. Types of lightning discharges that abruptly terminate enhanced fluxes of energetic radiation and particles observed at ground level, J. Geophys. Res.-Atmos., 122, 7582, https://doi.org/10.1002/2017JD026744, 2017b

[11] Chilingarian, A., Hovsepyan, G., Soghomonyan, S., Zazyan, M., and Zelenyy, M. Structures of the intracloud electric field supporting origin of long-lasting thunderstorm ground enhancements, Phys. Rev. D, 98, 082001, https://doi.org/10.1103/PhysRevD.98.082001, 2018

[12] Chilingarian, A., Soghomonyan, S., Khanikyanc, Y., and Pokhsraryan, D. On the origin of particle fluxes from thunderclouds, Astropart. Phys., 105, 54–62, https://doi.org/10.1016/j.astropartphys.2018.10.004, 2019. Chilingarian, A.,

Hovsepyan, G., and Sargsyan, B. Circulation of Radon progeny in the terrestrial atmosphere during thunderstorms, Geophys. Res. Lett.,47, e2020GL091155, https://doi.org/10.1029/2020GL091155, 2020a

[13] Chilingarian, A., Khanikyants, Y., Rakov, V. A., and Soghomonyan, S.: Termination of thunderstorm-related bursts of energetic radiation and particles by inverted intracloud and hybrid lightning discharges, Atmos. Res., 233, 104713, https://doi.org/10.1016/j.atmosres.2019.104713, 2020b

[14] Chilingarian, A., Karapetyan, T., Zazyan, M., Hovsepyan, G., Sargysan, B., Nikolova, N., Angelov, H., Chum, Jaroslav, and Langer, R.: Maximum strength of the atmospheric electric field, Phys. Rev. D, 103, 043021, https://doi.org/10.1103/PhysRevD.103.043021, 2021

[15] Parks, G., Mauk, K. B. H., Spiger, R, and Chin, J. X-ray enhancements detected during thunderstorm and lightning activities, Geophys. Res. Lett., 8, 1176–1179, 1981

[16] Eack, K. B., Beasley, W. H., Rust, W. D., Marshall, T. C., and Stolzenburg, M. Initial results from simultaneous observation of X-rays and electric fields in a thunderstorm, J. Geophys. Res., 101, 29637–29640, https://doi.org/10.1029/96JD01705, 1996

[17] Kelley, N. A., Smith, D. M., Dwyer, J. R. Splitt M., Lazarus, S., Martinez-McKinney, H., Hazelton, B., Grefenstette, B., Lowell, A., and Rassoul, H. K. Relativistic electron avalanches as a thunderstorm discharge competing with lightning, Nat. Commun., 6, 7845, https://doi.org/10.1038/ncomms8845, 2015

[18] Kochkin, P., van Deursen, A. P. J., Marisaldi, M., Ursi, A., de Boer, A. I., Bardet, Allasia, C., Boissin, J.-F., Flourens, F., and Østgaard, N. In-flight observation of gamma ray glows by ILDAS, J. Geophys. Res.-Atmos., 22, 12801–12811, https://doi.org/10.1002/2017JD027405, 2017

[19] Østgaard, N., Christian, H. J., Grove, J. E., Sarria, D., Mezentsev, A., Kochkin, P., Lehtinen, N., Quick, M., Al-Nussirat, S., Wulf, E., Genov, G., Ullaland, K., Marisaldi, M., Yang, S., and Blakeslee, R. J. Gamma ray glow observations at 20-km altitude, J. Geophys. Res.-Atmos.,124,7236–7254. https://doi.org/10.1029/2019JD030312, 2019

[20] Wilson, C. T. R.: The acceleration of particles in strong electric fields such as those of thunderclouds, Proc. Cambridge Philos. Soc., 22, 534–538, 1925

[21] Sihver, L., Ploc, O., Puchalska, M., Ambrožová, I., Kubančák, J., Kyselová, D., and Shurshakov, V., Radiation environment at aviation altitudes and in space, Radiat. Prot. Dos., 164(4):477-83 (2015). doi: 10.1093/rpd/ncv330

[22] Spurný, F., Ploc, O., Jadrníčková, I., Turek, K., Dachev, T., & Gelev, M. (2007). Monitoring of onboard aircraft exposure to cosmic radiation. Advances in Space Research, 40(11), 1551-1557 (2005)

[23] Ploc, O., Pachnerova Brabcova, K., Spurný, F., Malušek, A., & Dachev, T. (2011). Use of energy deposition spectrometer Liulin for individual monitoring of aircrew. Radiation Protection Dosimetry, 144(1-4), 611-614

[24] Dwyer, J. R., Smith, D. M., Uman, M. A., Saleh, Z., Grefenstette, B., Hazelton, B., & Rassoul, H. K. Estimation of the fluence of high-energy electron bursts produced by thunderclouds and the resulting radiation doses received in aircraft. Journal of Geophysical Research: Atmospheres, 115 (D9) (2020)

[25]Drozdov, A., & Grigoriev, A. (2013, February). Neutrons from thunderstorms at low atmospheric altitudes and related doses at aircraft. In Journal of Physics: Conference Series (Vol. 409, No. 1, p. 012246). IOP Publishing

[26]Tavani, M., Argan, A., Paccagnella, A., Pesoli, A., Palma, F., Gerardin, S., Flamini, E. et al. Possible effects on avionics induced by terrestrial gamma-ray flashes. Natural Hazards and Earth System Science, 13(4), 1127–1133 (2013)

[27] Slegl, J., Langer, R., Brunclík, T., Masek, P.; Strhárský, I., Ambrozová, I., Chum, J., and Ploc, O., Spectrometry of High-Energy Photons on High Mountain Observatory Lomnicky Stit During Thunderstorms. Rad. Prot. Dos. (2022), Vol. 198, No. 9–11, pp. 623–627

[28] Šlegl et al. 2019 Šlegl, J., Minářová, J., Kuča, P., Kolmašová, I., Santolík, O., Sokol, Z., et al. Response of the Czech RMN network to thunderstorm activity. Radiation Protection Dosimetry, 186(2-3), 215-218 (2019)

[29] Kolmašová et al. 2022 Kolmašová, I., Santolík, O., Šlegl, J., Popová, J., Sokol, Z., Zacharov, P., ... & Strhárský, I. Continental Thunderstorm Ground Enhancement observed at an exceptionally low altitude. Atmospheric Chemistry and Physics Discussions, 1-21 (2022)

[30] Kákona, M., Šlegl, J., Kyselová, D., Sommer, M., Kákona, J., Lužová, M., Štěpán, V., Ploc, O., Kodaira, S., Chroust, J., John, D., Ambrožová, I., & Krist, P. AIRDOS — open-source PIN diode airborne dosimeter. In Journal of Instrumentation, Vol. 16, Issue 03, p. T03006 (2021). IOP Publishing. https://doi.org/10.1088/1748-0221/16/03/t03006

[31] Velychko, O., Ambrožová, I., Kákona, M., Ploc., O., Characterisation of AIRDOS-C detector for measurement of high-energy events in the atmosphere, Rad. Prot. Dos*.,* Volume 198, Issue 9-11, August 2022, Pages 604–610. https://doi.org/10.1093/rpd/ncac105

[32] Kyselová, D., Mikeš, J., Štěpán, V., Ambrožová, I., Benton, E. R., Sommer, M., ... & Reitz, G. Measurements of radiation induced by a spark discharge under laboratory conditions. Radiation Measurements, 137, 106420 (2020)

[33] Jakub Kákona, Martina Lužová, Martin Kákona, Marek Sommer, Martin Povišer, Ondřej Ploc, Roman Dvořák, Iva Ambrožová, Measurement of the Regener–Pfotzer maximum using different types of ionising radiation detectors and a new telemetry system tf-atmon, Radiation Protection Dosimetry, Volume 198, Issue 9-11, August 2022, Pages 712–719

[34] Štěpánová, D., Mikeš, J., Štěpán, V., Krbal, M., & Ploc, O. Vertical Dosimetric Measurement of Electric Discharge Induced at Lightning Impulse Voltage Generator. Radiation Protection Dosimetry, 198(9-11), 617-622 (2022)

[35] Ambrožová, I., Beck, P., Benton, E. R., Billnert, R., Bottollier-Depois, J. F., Caresana, M., et al. (2020). REFLECT–research flight of EURADOS and CRREAT: intercomparison of various radiation dosimeters onboard aircraft. Radiation measurements, 137, 106433

[36] Kákona, J., Mikeš, J., Ambrožová, I., Ploc, O., Velychko, O., Sihver, L., and Kákona, M. In situ ground-based mobile measurement of lightning events above central Europe, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2022-379, 2022

[37] Rakov, V.A., Lightning Physics and Effects. Cambridge University Press, Online publication date: June 2013, Print publication year: 2003, ISBN: 9781107340886, DOI: https://doi.org/10.1017/CBO9781107340886

[38] Lopez, J.A., Spatiotemporal dimension of lightning flashes based on three-dimensional Lightning Mapping Array. Atmos. Res. 197 (2017), 255-264. https://doi.org/10.1016/j.atmosres.2017.06.030

[39] Kudela, K., Chum, J., Kollárik, M., Langer, R., Strhárský, I. and Base, J. Correlations Between Secondary Cosmic Ray Rates and Strong Electric Fields at Lomnický stít. J. Geophys. Res. Atmos. 122, 10,700– 10,710 (2017)

[40] Chum, J., Langer, R., Base, J., Kollárik, M., Strhárský, I., Diendorfer, G. and Rusz, J. Significant enhancements of secondary cosmic rays and electric field at the high mountain peak of Lomnický Stít in High Tatras during thunderstorms. Earth Planets Space 72, 28 (2020)

[41] Sato, T., Iwamoto, Y., Hashimoto, S., Ogawa, T., Furuta, T. et al. Features of Particle and Heavy Ion Transport code System (PHITS) version 3.02. J. Nucl. Sci. Technol. 55, 684–690 (2018)
[42] Iva Ambrožová, Martin Kákona, Hana Kyznarová, Petr Novák, Jakub Kákona, Jan Chroust, Jakub Šlegl, Miroslav Tesař, Olena Velychko, Ondřej Ploc. Monitoring of ionizing radiation from thunderstorms in Bohemian Forest using standalone device GEODOS (submitted to Silva Gabreta, August 2023)