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Monitoring of ionizing radiation from thunderstorms in Bohemian Forest using standalone device GEODOS

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Abstract

Various high-energy atmospheric phenomena can be associated with thunderstorms and they can also be detected on the ground as increases in ionizing radiation. However, their mechanisms are not yet fully understood. At present, there are only a few ground measurements, mostly limited to high-mountain observatories or occurrences during winter thunderstorms in Japan. To increase the number of observations and to measure high-energy gamma radiation induced in thunderstorms in hard-to-reach terrains with no support infrastructure, GEODOS – a small, standalone device equipped with an inorganic scintillation crystal and SiPM – was developed. During the summer 2021, three GEODOS units were placed in Bohemian Forest on the Poledník hill and in the area around the Poledník hill. In the paper, we introduce the system and discuss the obtained results.

Key words: thunderstorm, lightning, ionizing radiation, TGE, TGF, GEODOS

Introduction

Increases in detected radiation associated with lightning activity have been observed both in space and on the ground. Terrestrial gamma-ray flashes (TGF), observed mostly in space, are intense submillisecond bursts of X-rays and gamma-rays with energies up to several tens of MeV produced by lightning discharges (Fishman et al. 1994, Tavani et al. 2011, Celestin et al. 2012, Tavani et al. 2013, Shmatov 2015).

Electrons produced via cosmic rays or induced by radon decay are accelerated by the electric field inside the thundercloud, forming relativistic runaway electron avalanches (RREA) (GUREVICH et al. 1992). These avalanches emit bremsstrahlung X-rays, and the resulting enhancement of radiation can be detected on the ground. These phenomena are referred to as thunderstorm ground enhancements (TGE), long(-duration) bursts, or gamma-ray glows (e.g., TORII et al. 2009, TORII et al. 2011, CHILINGARIAN & MKRTCHYAN 2012, DWYER et al. 2012, DWYER et al. 2015, WADA et al. 2018a, CHILINGARIAN et al. 2019a, YUASA et al. 2020, DINIZ et al. 2021, KURIYAMA et al. 2023). Typical duration of these bursts ranges from seconds to a few minutes, and the energy can reach values up to tens of MeV. These events can be formed by gamma radiation as well as other particles such as electrons and neutrons (CHILINGARIAN et al. 2010). The mechanism of various high-energy atmospheric phenomena associated with thunderstorms is very complex, and some details are not yet fully understood.

On the ground, TGEs have been mostly detected at high altitudes (above approximately 2500 m a.s.l.) (e.g., TORII et al. 2009, TSUCHIYA et al. 2009, CHILINGARIAN et al. 2011, CHILINGARIAN et al. 2012, CHILINGARIAN & MKRTCHYAN 2012, GUREVICH et al. 2013, CHILINGARIAN et al. 2019b, CHUM et al. 2020, SLEGL et al. 2022) or at sea level during winter thunderstorms in Japan (e.g., TSUCHIYA et al. 2007, TORII et al. 2011, ENOTO et al. 2017, WADA et al. 2019, WADA et al. 2021), where the base of the thundercloud is much lower than in summer thunderstorms.

To observe high-energy radiation associated with thunderstorms on the ground, the cloud region with a negative charge has to be close to the detector due to the attenuation of radiation in the air. TORII et al. (2011) estimated the radiation source as a downward hemispherical surface with a radius of 700 m centered at an altitude of 1000 m. TSUCHIYA et al. (2009), who detected both high-energy gamma rays and electrons during a thunderstorm at the Norikura cosmic-ray observatory in Japan (2770 m a.s.l.), estimated the source to be located at a distance of 60–130 m from the detector. CHILINGARIAN et al. (2010) assumed the probable cloudbase height above the ground to be 100–150 m for the large TGE measured with multiple detectors at the Aragats Space Environmental Center (3250 m a.s.l.) during an event on September 19, 2009. The distance to the cloud base for the events detected at Aragats in 2017 ranged from several tens to several hundred meters (CHILINGARIAN et al. 2019b).

With the exception of high-mountain observatories or winter thunderstorms in Japan, there are a limited number of observations of these high-energy radiation atmospheric phenomena (e.g., SLEGL et al. 2019, KOLMASOVA et al. 2022, SLEGL 2022).

Several studies have reported that the increases in high-energy count rates are associated with precipitation rather than storm electrification (SUSZCYNSKY et al. 1996, MALLICK et al. 2012, MONTANYÀ et al. 2014, FABRO et al. 2016). The count rate increases were due to the rain and washout of radon progeny (products of the chain of 238U and 232Th) from the atmosphere.

Enhancements with short- and long-lasting responses were detected by the Early Warning Network of the Radiation Monitoring Network of the Czech Republic (SLEGL et al. 2019). These events could not be explained by radon progeny alone. Other events in central Europe were detected on Milešovka hill in the Central Bohemian Highlands (KOLMASOVA et al. 2022, SLEGL 2022).

To increase the probability of detecting the events associated with thunderstorms, multiple detectors that can be placed in various locations are desirable. Gamma-ray spectrometers based on scintillation detectors are typically used for the detection of X-rays and gamma-rays. However, most commercially available gamma spectrometers are not well-suited for measuring radiation associated with high-energy atmospheric phenomena. They often do not provide time-resolved data and only record spectra integrated over long time periods (e.g., 10 minutes). Additionally, their energy range is limited to a few MeV (usually about 3 MeV). Specially designed spectrometers with an extended energy range and the ability to record individual events require a power supply or can operate on batteries only for a limited time period (usually several hours) (WADA et al. 2018b, YUASA et al. 2020, SLEGL et al. 2022).

Therefore, our aim was to develop a detector (called GEODOS) capable of measuring high-energy (up to several tens of MeV) gamma radiation induced by thunderstorms in areas, where the probability of thunderstorms is expected to be higher, but which lack the support infrastructure required by other devices.

GEODOS is a small, standalone device equipped with a scintillation crystal (e.g. NaI(Tl)) for measuring gamma radiation up to several tens of MeV. The device is relatively inexpensive compared to other spectrometers and can be deployed in various hard-to-reach areas such as forests. GEODOS is equipped with solar cells for charging the device battery, reducing the probability of the need for an external power supply or regular battery replacements.

Three GEODOS units were placed in the Bohemian Forest during the summer of 2021 in the area around Poledník hill, and ionizing radiation was continuously measured for about two months. The obtained results are presented, and several candidates for TGE or TGF are discussed in more detail.

MATERIAL AND METHODS

GEODOS

The device GEODOS (KÁKONA 2024) is an ionizing radiation detector based on a scintillation crystal and a Silicon photomultiplier, similar to the AIRDOS-C detector (VELYCHKO et al. 2022). In our case, we used NaI(Tl) cylindrical scintillation crystals, 17 ± 1 mm in diameter and 30 mm in length. The crystal, together with the SiPM, is placed inside a tin box for the purpose of shielding against electromagnetic field (Fig. 1b).

All components, including the detection unit, temperature and pressure sensors, GPS, battery management, and IoT modem, are placed inside a plastic box with dimensions of $25 \times 18 \times 10$ cm^3, as shown in Fig.1a. The modem enables connection to the Internet of Things (IoT). Approximately 200 bytes of data can be transferred per day, allowing for regular checks of the device's battery voltage, temperature, and ionizing events counts to ensure proper operation.

The electronics divide the measured energy into 250 channels. The dynamic range is limited by the battery voltage, which can cover a relatively large range from hundreds of keV to tens of MeV, depending on the specific detector unit and chosen voltage. In this study, units with an energy range of 0.3–18 MeV were used. The resolution of the device is 70 keV (channel width). The detectors were calibrated using several radionuclide sources emitting gamma radiation, as described in (VELYCHKO et al. 2022).

Data is integrated over 15 seconds and stored on an SD card. For deposited energies higher than 0.8 MeV, the time and energy of each individual event are recorded with a time resolution of 65 μs. Using 2 GB SD card, the measurement can run for 6 months.

Three GEODOS units (with serial numbers 10, 13, and EC) were placed in the Bohemian Forest in the area around Poledník hill to continuously measure radiation during the summer and autumn of 2021 (July–October). The positions of the individual units can be seen in Fig. 2a. GEODOS 10 was placed directly in the Poledník tower (1351 m a.s.l.), 1.7 m above the roof (Fig. 2b). GEODOS EC and GEODOS 13 were mounted on a tree, 2.5 m above the terrain (Fig. 2c), approximately 1 km and 2 km away from the tower, respectively.

Environmental data

Besides data about radiation monitoring measured with GEODOS, we evaluated additional information on environmental conditions.

Evaluation of meteorological conditions was carried out using data provided by meteorological radars from the Czech Weather Radar Network (CZRAD) operated by Czech Hydrometeorological Institute (CHMI) (Kyznarová & Novák 2016), in more detail (Novák & Kyznarová 2016), and lightning detection network LINET operated by Nowcast GmbH. CZRAD doppler meteorological radars have been manufactured by Vaisala Oyj as type WRM 200, their transmitter contains magnetron to create microwave pulses of sufficient

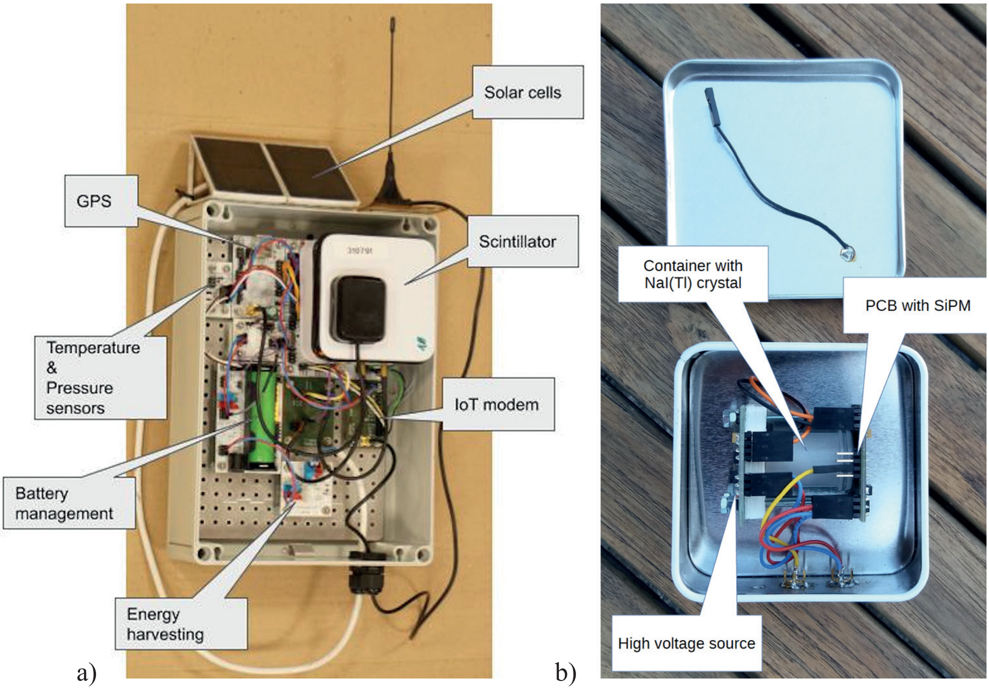


Fig. 1. a) GEODOS, including the detection unit (scintillator), temperature and pressure sensor, GPS, battery management, IoT modem, and solar cells. b) The details of the interior of the detection unit (photo: M. Kákona).

energy at the wave length (5630 MHz Brdy, 5645 MHz Skalky) and radar pulses are transmitted simultaneously in two perpendicular (horizontal and vertical) polarizations. This enables better distinguishing of meteorological and non-meteorological targets. For use in this study, spherical radar volumetric data have been interpolated into cartesian grid with 1×1 km horizontal resolution and 0.5 km vertical resolution. Operator of LINET lightning detection network (BETZ et al. 2009) provides following technical parameters: detection efficiency 98%, location accuracy <100 m.

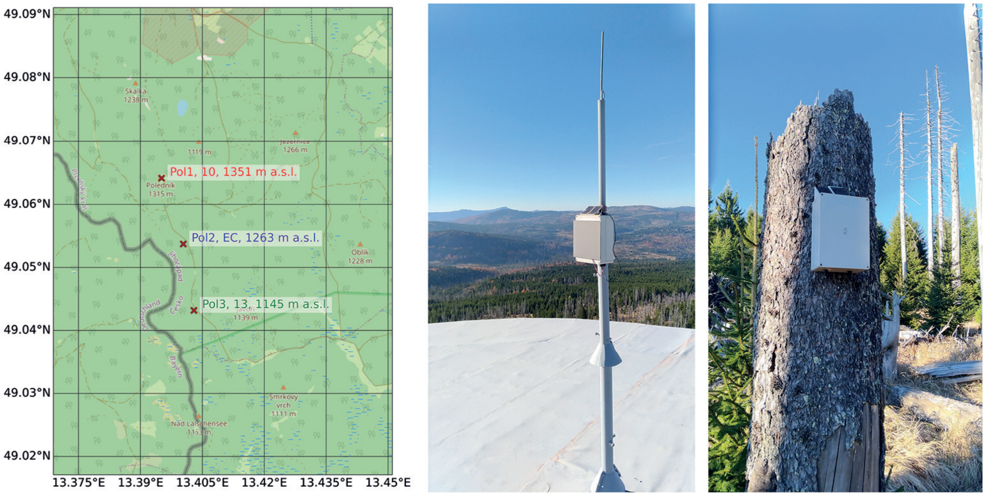
Information about nearby lightning activity was also obtained from Blitzortung, the World-Wide Low-Cost Community-Based Time-of-Arrival Lightning Detection and Lightning Location Network (WANKE et al. 2014).

Meteorological data in 10 minutes interval such as air temperature both close to the soil surface and at 2 m height (Pt100 sensors), air humidity (RVT13 sensor – Fiedler AMS), precipitation (SR03 – Meteoservis) at the Poledník tower were obtained from the Institute of Hydrodynamics of the Czech Academy of Sciences.

Data processing

First, it was necessary to develop a method to identify and distinguish possible candidates for TGE and TGF. These events are characterized by rapid increases and decreases in radiation levels lasting from milliseconds to minutes. TGFs are very short, hundreds of microseconds up to a millisecond, and TGEs are minutes-long events.

During data processing, we searched for deviations in the time series of particles registered with the detector. The aim was to find time intervals with rapid changes and distinguish them from increases caused by radon progeny washout, which are characterized by a gradual



a) b) c)

Fig. 2. a) Three GEODOS units placed around Poledník (with altitude information); b) GEODOS placed in the Poledník tower; c) GEODOS units mounted on a tree (photo: M. Kákona).

increase and a long-lasting decrease in the number of registered particles. To determine the presence and time of the event, two approaches depending on the parameters were proposed – Linear Combination of Moving Averages (LCMA) and Cumulative Sum (CUSUM) (MISHRA et al. 2015). These methods are statistical methods used to detect changes in the characteristics of time series (CHERTOK et al. 2016). Assuming initially that the measurement results are random variables distributed according to the Poisson law, the methods allowing determination of how distribution parameters change if some event occurs have been developed. The goal was to find these changes that characterize the onset and intensity of the event.

For each statistic, the corresponding parameters were selected. For LCMA, a linear combination of simple moving average and exponential moving average was used. Not only the parameters of the averages were selected, but also the coefficients of the linear combination. The results obtained with the proposed method were tested and compared with the results obtained with other more sensitive detectors, e.g., the performance of the GEODOS detector was compared with the results of the SEVAN detector, measuring simultaneously at Lomnický Štít (VELYCHKO et al. 2023). Data from another type of gamma-ray spectrometer – RT51 (SLEGL et al. 2022) continuously measuring at Lomnický štít were tested using this method, which resulted in the finding of almost 40 events in the period from April 2022 to December 2023. This enabled to obtain sufficient statistics for analysis and optimizing the parameters of the used method. For each event, the time and duration of the event, its intensity, and weather conditions were monitored.

These analyses allowed the development of Python scripts for the automatic processing of measurement data acquired from GEODOS.

RESULTS AND DISCUSSION

Using the developed methods described above, several events were found as possible candidates for TGE or TGF, namely events measured with GEODOS 10 during August 15th and 16th, and with GEODOS 13 during August 7th and 22th. Further detailed investigation revealed that some of these count rate increases (August 7th and 22th) were only due to rain and radon progeny washout. The relatively rapid increase could be attributed to sudden rainfall. Such increases in radiation followed by exponential decay lasting 2–3 hours are typically associated with the concentrations of radon progeny resulting from their washout during rainfall.

Figure 3 shows the count rates measured with all three GEODOS units during August 15th and 16th, 2021, along with information about the distance of nearby lightning events recorded with Blitzortung and precipitation measured by rain gauge at the meteorological station near the Poledník tower. In the image, gradual increases and decreases in ionizing radiation levels during and after the rain are clearly observed for all units. These increases are due to the washout of radon progenies and following decay of radon's daughter products. Additionally, steep increases in ionizing radiation recorded with GEODOS 10 are also visible when lightning activity is closest to the ionizing radiation sensor. GEODOS EC detected a flux of ionizing radiation approximately 30% lower than GEODOS 10 and GEODOS 13. This can be due to the manufacturing tolerance of the SiPM, which, in this piece, has a breakdown voltage 0.3 V higher, causing a nearly 30% loss in amplification. Effectively, this results in the detection threshold for this piece being shifted by one channel, thus about 70 keV higher.

The developments of rainfall intensities in mm/h at individual GEODOS unit sites are depicted in Fig. 4. The rainfall intensities were interpolated from 5-minute radar measurements of Constant Altitude Plan Position Indicator (CAPPI) 2 km levels into 1-minute values. As can be seen, the rainfall at all three sites was similar and occurred at the same time, as could be expected considering the spatial resolution of the radar data and the distance of each location.

Meteorological analysis of the event on August 15th, 2021 shows that the peak at GEODOS 10 detector occurred in a time period when border of a convective system was moving over the detector site. During this period only one stroke was detected by LINET network in the 5 km surrounding of GEODOS detector sites (Fig. 5a). It was a weak CG stroke with lightning current amplitude of -2 kA (which means the stroke carried negative charge to the ground with the lightning current amplitude of 2 kA) at 18:13 UTC at a distance 4.8 km from GEODOS 13 detector.

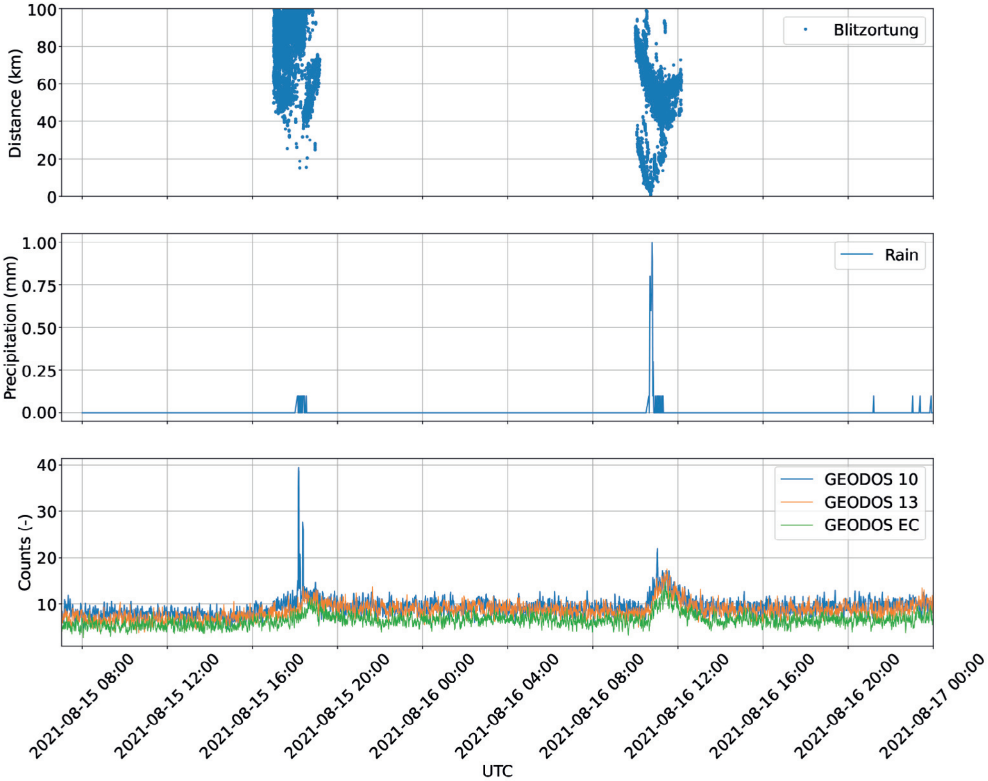


Fig. 3. Count rates measured with three GEODOS detectors placed around Poledník together with information about the distance of nearby lightning discharges (August 15th, 2021, and August 16th, 2021) and precipitation measured by rain gauge at the meteorological station near the Poledník tower.

Rest of the strokes occurred in greater distance that 5 km from any of the detectors. Rainfall intensity at the sites of all three detectors was only light.

Next event occurred on August 16th, 2021. During that period around 10:45 UTC rainfall intensity estimated from CZRAD was reaching values over 50 mm/h which is already a rather high rainfall intensity. Closest lightning stroke occurred at a distance 248 m from GEODOS 13 site and it was a weak CC stroke with lightning current amplitude 2 kA. Estimates of lightning current amplitudes are inaccurate, especially for CC strokes. However, both CC and CG strokes in the 5 km surrounding during this high-energy radiation event seemed rather weak, reaching values 12 kA and less.

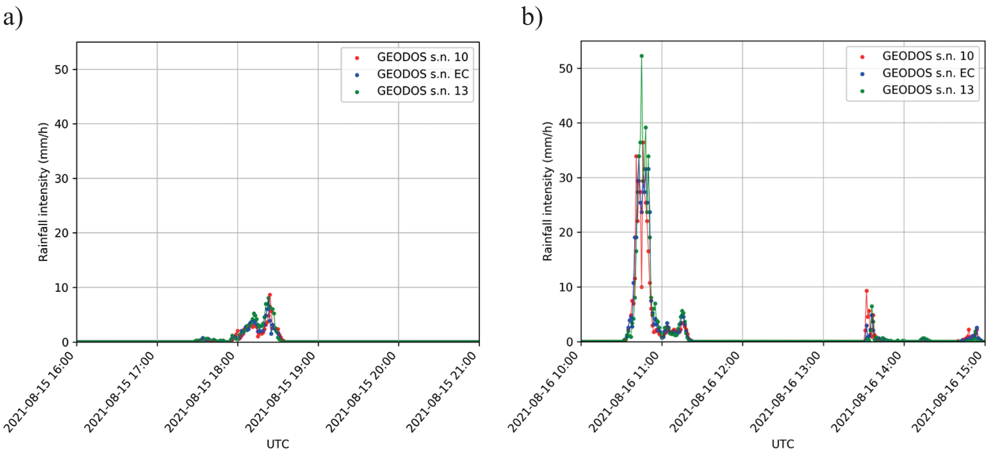


Fig. 4. Developments of rainfall intensities interpolated from 5-minute radar measurements of CAPPI 2 km levels into 1-minute values for individual detector sites (GEODOS 10, GEODOS EC, GEODOS 13) during two analyzed days with TGE events; a) August 15th, 2021, b) August 16th, 2021.

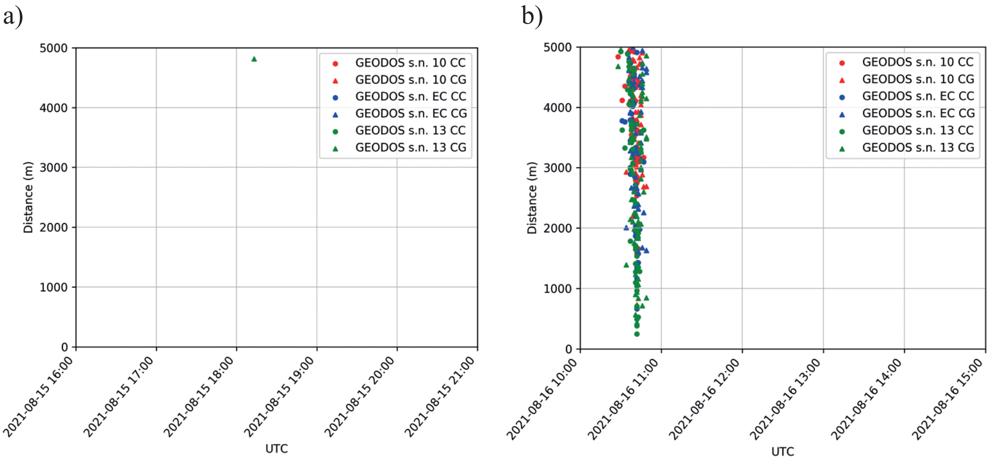


Fig. 5. Distance of individual CC and CG lightning strokes from the three GEODOS detector sites (GEODOS 10, GEODOS EC, GEODOS 13) during two analyzed events; a) August 15th, 2021, b) August 16th, 2021.

The courses of lightning strokes detected by LINET network are depicted in Fig. 5. Individual figures show the distance of CC and CG strokes from the GEODOS unit sites during high-energy radiation occurrences.

Based on the temperature and humidity measured at the Poledník hill, the dew point was calculated, and from this, the cloud base was estimated to be 226 m and 198 m above the terrain for events registered on August 15th and August 16th, respectively.

The two events observed on August 15th and August 16th, 2021, using GEODOS 10 placed at the Poledník tower are analyzed in more details in the following text. Figure 6 displays a temporal detail of the event on August 15th. Upon closer examination, it can be observed that within less than half an hour, there were three increases in ionizing radiation flux. During the first increase, particles with energies above approximately 800 keV were detected within a very short time interval of tens of milliseconds. Throughout the entire 15-second measurement interval, there was an increase in particle flux, mainly in the energy range of approximately 350 to 550 keV, followed by a rapid decrease within one minute. This decline may indicate subsequent radioactive decay induced by the activation of surrounding materials. The evolution of detected energies over time is shown in Fig. 7.

Figure 8 shows a detail of a cluster of particles, which is visible in Fig. 6. It can be observed that the entire event lasted approximately 40 ms. It is important to note that not all particles may be captured here, as the GEODOS device is only capable of detecting a single particle within a 65 μs time interval. The detection of an ionizing radiation increase lasting tens of milliseconds is atypical for both TGE and TGF. For TGF, typical bursts last from microseconds to millisecond. In contrast, the duration of TGE events ranges from seconds to minutes.

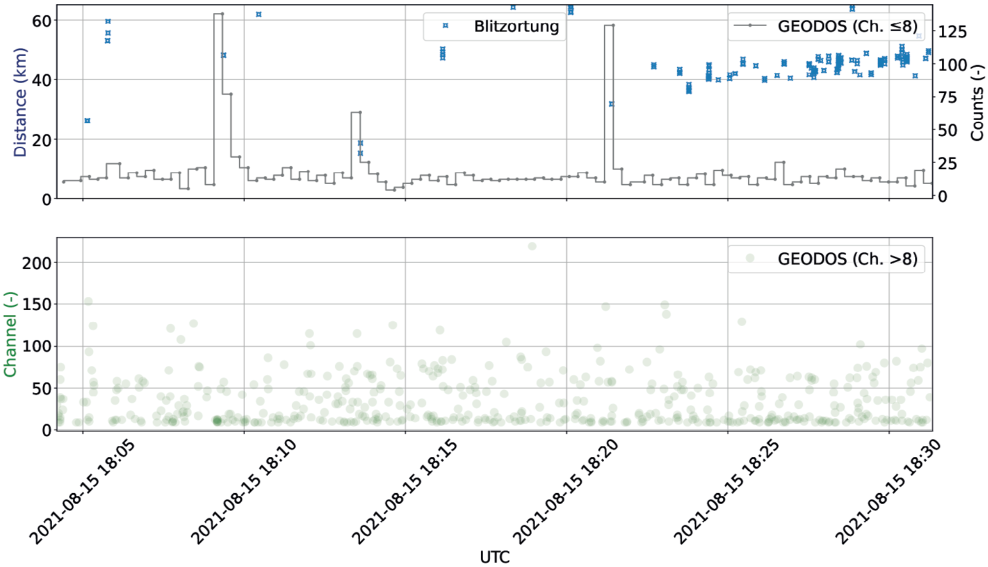


Fig. 6. The event captured by the GEODOS 10 located at the Poledník tower on August 15th. The upper image displays the distance from lightning discharges and the counts of detected ionizing radiation particles in lower energy channels of the detector. The lower image shows individual detected events from the ninth channel and above. The individual points are semi-transparent, allowing for the observation of clusters of events over time.

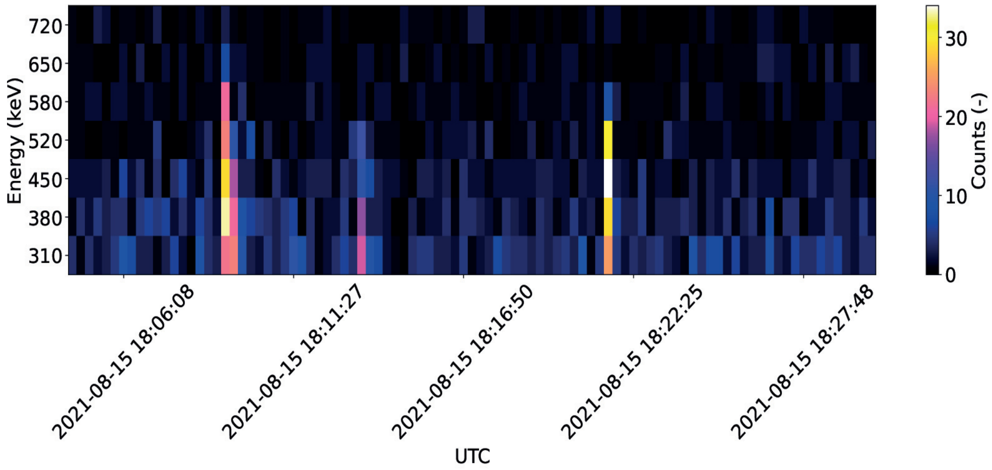


Fig. 7. Evolution of detected energies in time for lower channels (Ch.≤8).

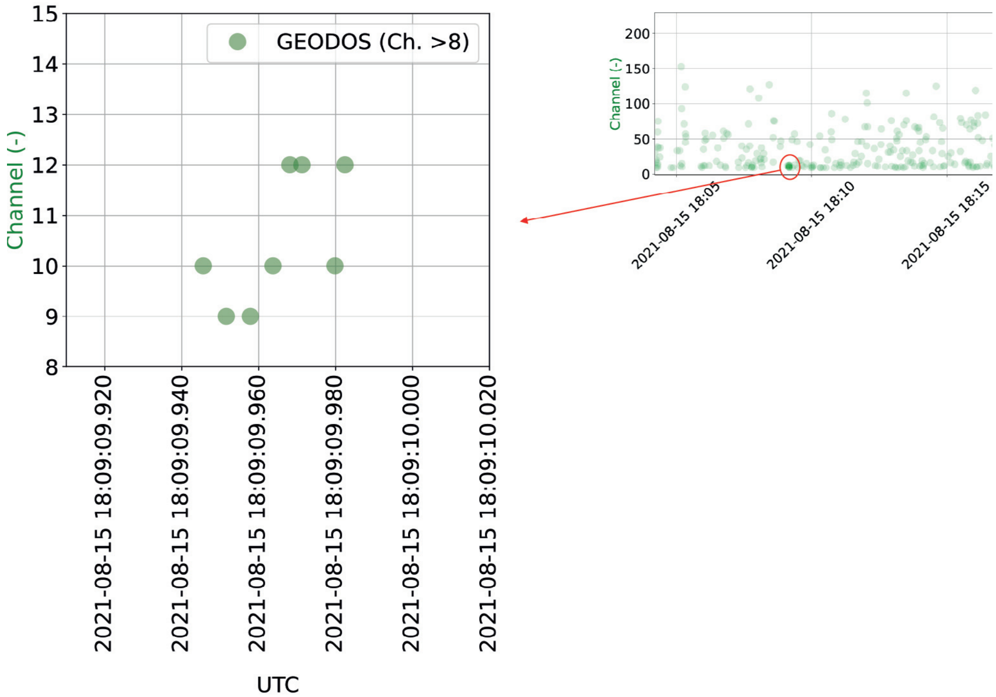


Fig. 8. Detail of the cluster of measured ionization events. The graph displays individual recorded particles. The time uncertainty is ±100 µs and is achieved for detections with absorbed energy above channel 8 only. During a time interval of 65 µs, the device is capable of detecting only a single particle.

From the analysis of the meteorological situation and data from the lightning detection networks, it appeared that thunderstorm activity in close proximity to the detector (<10 km) was relatively weakened, rather none, during the detected radiation events. However, previous work (KÁKONA et al. 2023) indicated that lightning could be extensive, covering distances of even tens of kilometers. In (KÁKONA et al. 2023), it was demonstrated the detection of lightning, where the lower estimate of the distance between the two farthest points was 80 km. Additionally, it was shown that the Blitzortung network did not detect all lightning channels along the entire length of the discharge.

To see the evolution of storms over time and in more distant areas, Figure 9 displays a map of atmospheric discharges detected by LINET network up to 60 km and the times of detections that are closest in time to the detected radiation increases.

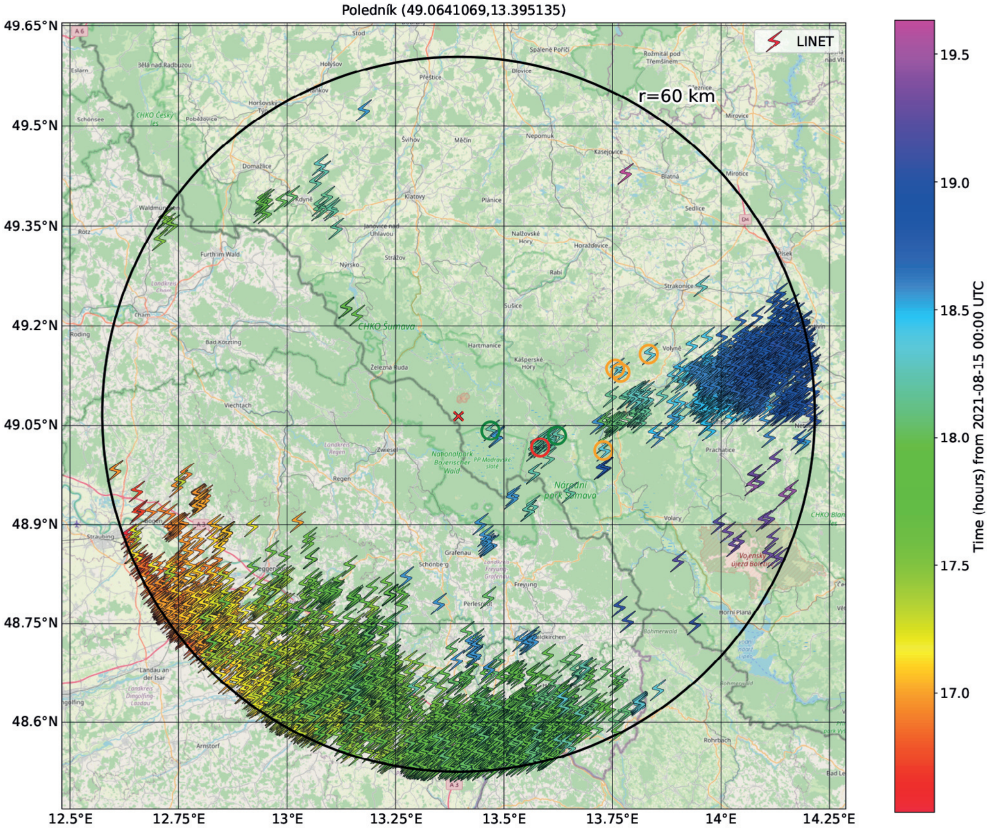


Fig. 9. Map of discharges detected by LINET network in 60 km proximity. The position of device GEODOS 10 is marked in the center with a red cross. The storm moves from South-West to North-East. A decrease in activity is noticeable as the storm passes over the mountain ridge. The circles correspond to the time of three increases in radiation measured with GEODOS 10 (seen in Fig. 8 or 9) - red: 2021-08-15 18:09:09; green: 2021-08-15 18:13:35; orange: 2021-08-15 18:21:24.

From the telemetry data obtained from GEODOS 10, it was observed that during or just before the radiation events, there must have been discharges near the sensor, leading to damage to the electronics responsible for charging the device's battery from the solar panel. Figure 10 shows the voltage measured on the batteries. Around 18:05 UTC, voltage fluctuations occurred, followed by a complete interruption of the voltage measurement and an interruption of charging the battery.

The device experienced damage to its electronic components responsible for charging the battery from the solar panel. Despite this damage, it did not affect the device's measurement capabilities. The device continued to operate and successfully recorded a radiation event the following day. However, the damage led to a gradual discharge of the battery. After several days, the battery was completely drained, resulting in an interruption of the measurement.

It is important to note that during the period of electronic damage, the device's performance in detecting radiation remained unaffected. The battery voltage of the device does not influence its dynamic range, it was compensated by DC/DC converter.

However, during the time of electronic damage (around 18:05 UTC), no increased radiation was detected and no lightning discharge was detected. It is possible that very weak lightning discharges are not detected by Blitzortung or even by LINET despite the fact that LINET lightning detection is more efficient. It is likely that weak discharges continued undetected by the LINET and Blitzortung systems, similar to the case of the solar panel being affected.

The other event detected with GEODOS 10 on August 16th, 2021, was less significant. From Fig. 11, it is evident that the increase around 11:00 is not associated with the rainfall around 10:45.

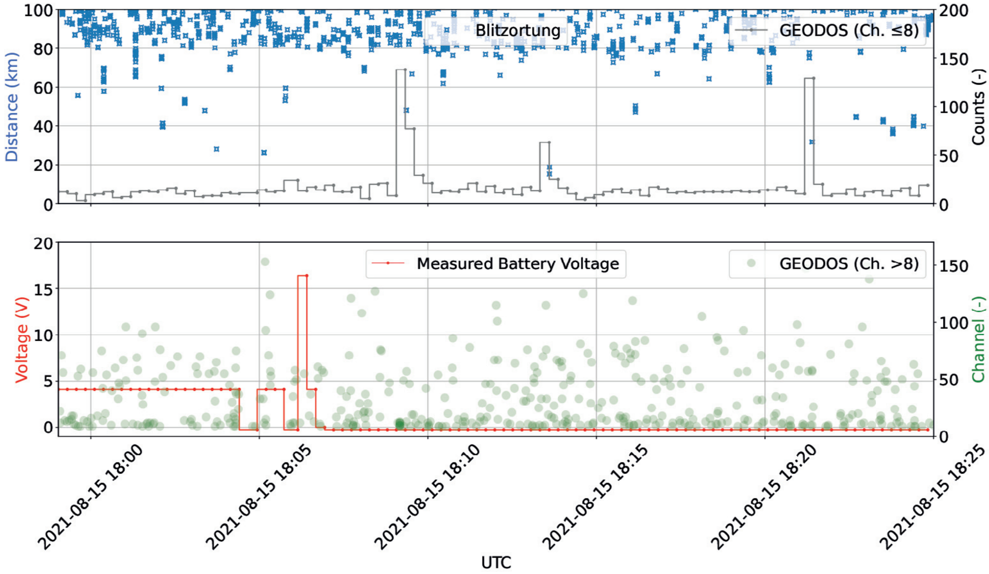


Fig. 10. Battery voltage (lower graph) with corresponding distances from discharges and ionizing radiation events.

As can be seen in Fig. 12, there was an increase observed only in the first two channels. Since no noticeable increase was detected in the higher channels during this event, it is impossible to determine a more precise event time. For energies lower than 0.8 MeV, GEODOS provides a temporal resolution of only 15 seconds.

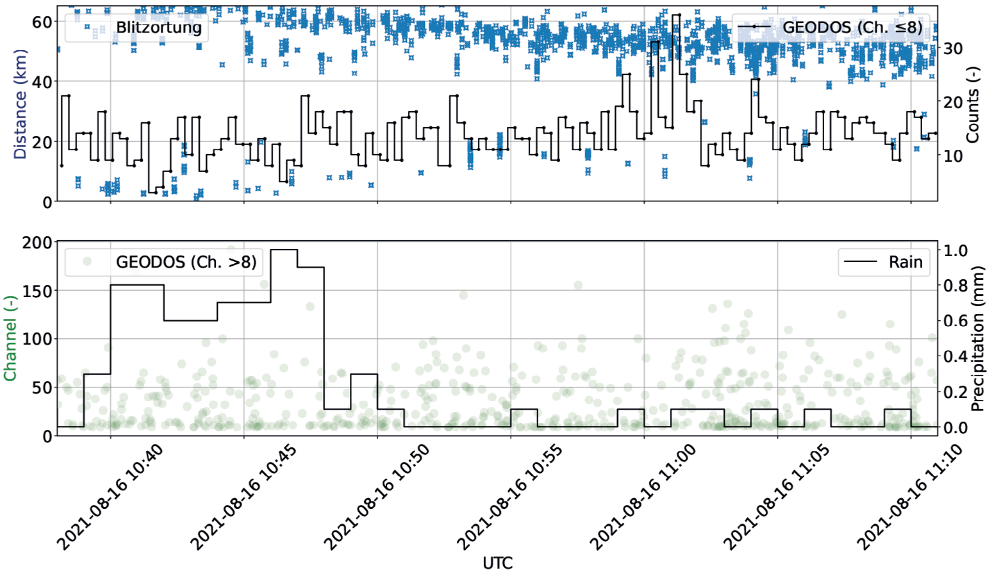


Fig. 11. The event captured by the GEODOS 10 located at the Poledník tower on August 16th. The upper image illustrates the distance from lightning discharges and the counts of detected ionizing radiation particles in the detector's lower energy channels. The lower image presents individual detected events from the ninth channel and above, alongside precipitation measured by rain gauge at the meteorological station near the Poledník tower.

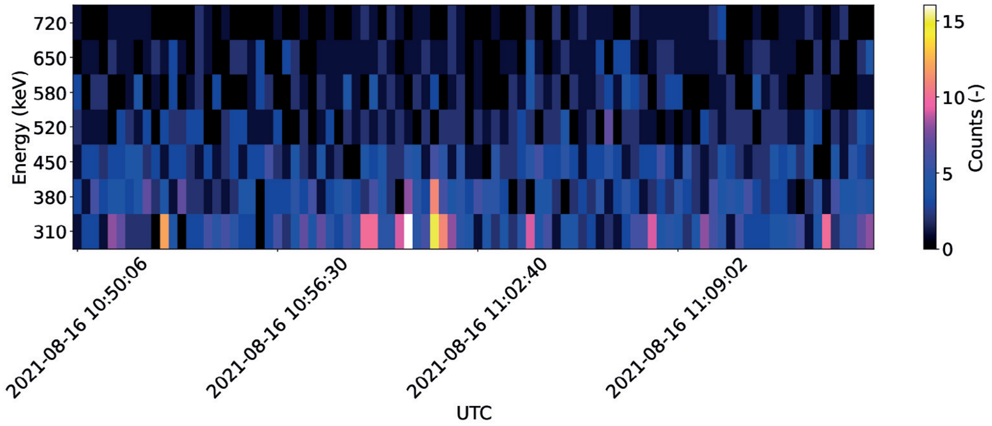


Fig. 12. Evolution of detected energies in time for lower channels (Ch.≤8).

Both events have in common that the increase in ionizing radiation occurred when lightning activity was moving away from the Poledník site. Furthermore, in both cases, the increase was detected only at the lookout tower, in the place with the highest altitude (1351 m a.s.l.). Detectors placed in lower altitudes (1263 m and 1145 m a.s.l.) did not detect the increases. For the observation of high-energy radiation associated with thunderstorms, higher altitudes, where the cloud base is closer to the detector, seem to be more suitable. The detected radiation had relatively low energies, and the direction from which it originated was unknown. Since no lightning strike was directly detected at the location of the detector, it is possible that the radiation was coming from the side. Further improvements and developments in various sensors, such as those capable of measuring the distribution of the electric field and operating on batteries, will be needed.

Based on measurements made during the summer of 2021, several enhancements were implemented in an upgraded version of GEODOS. These included increasing the overvoltage for enhanced amplification, replacing the batteries with ones that allow recharging even below freezing point, increasing the number of ADC channels for improved energy resolution, and extending the conversion time to 104 microseconds

CONCLUSIONS

A standalone device GEODOS was developed for continuous monitoring of radiation in remote locations without infrastructure. It has been demonstrated that GEODOS is capable of detecting changes in radiation and potential radiation events related to thunderstorm activity. During the measurement period in summer 2021, two candidates for TGE or TGF were detected at relatively low altitudes (approximately 1350 m above sea level) in the Bohemian Forest area. The increase in radiation lasted tens of ms, which is quite atypical for both TGE and TGF. In addition, the lightning discharges detected by LINET and Blitzortung networks did not occur in close proximity (less than 2 km) to the sensor which recorded increases in ionizing radiation. On the contrary, a closer sensor placed at a lower elevation did not register an increase.

Currently it is too soon to make any final conclusions regarding temporal and spatial relations between lightning discharges as detected by LF lightning detection networks and radiation detected by GEODOS sensors. These relations will need to be studied further on a larger dataset.

Further measurements and combining data from multiple sensor types will be necessary to understand such events better. It is a future challenge to install additional sensors in hard-to-reach areas without infrastructure where radiation measurements in thunderstorms have not been conducted so far.

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