**Threshold Atmospheric Electric Fields for Initiating Relativistic Runaway Electron**

**Avalanches: Theoretical Estimates and CORSIKA Simulations**

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**Abstract**

We examine the threshold Atmospheric Electric Field (Eth) needed to initiate a runaway avalanche process in Earth's atmosphere. We compare the traditional, thirty-year-old theoretical threshold value with its recently updated value, along with the threshold derived from CORSIKA-simulated avalanches (Ez). The altitude dependence of these threshold values is analyzed, considering changes in air density and their effects on avalanche development. This study is vital for understanding high-energy atmosphericphenomena in both the lower and upper atmosphere, including thunderstorm ground enhancements (TGEs) and gamma glows, as well as for refining AEF models based on particle flux measurements.

**Short Summary**

Thunderstorms can accelerate particles in the atmosphere, producing bursts of radiation at

the ground. We investigated how strong the electric field inside a cloud must be to start

such events. Using advanced computer simulations and comparing with measurements

from mountain stations, we found that fields must be stronger than earlier theory

suggested. Our results improve understanding of storm electricity and its role in natural

radiation.

**Highlights**

* Introduces a refined framework for determining threshold atmospheric electric

fields (Eth) needed to initiate relativistic runaway electron avalanches (RREAs)

and thunderstorm ground enhancements (TGEs).

* Compares classical (Eth ≈ 2.80 × n) and updated (Eth ≈ 2.67 × n) theoretical

thresholds with altitude-dependent thresholds derived from CORSIKA simulations.

* Demonstrates that realistic avalanche development requires fields 15–22%

stronger than theoretical values, depending on altitude and air density.

* Provides a reproducible simulation methodology for integrating experimental

particle flux measurements into atmospheric electricity models across multiple

research stations.

**Introduction**

Free electrons are abundant in the troposphere. The altitude where their density reaches

its highest point—called the Regener–Pfotzer maximum—depends on various factors,

including the geomagnetic cutoff rigidity (Rc), the type of particles being measured, and

the phase and strength of the solar cycle. Recent observations, supported by PARMA4.0

calculations (Sato, 2016), show that at middle to low latitudes (Rc = 3–8 GV), the highest

flux of charged particles occurs at altitudes around 12–14 km (see Fig. 4 in Ambrozova et

al., 2023).

Atmospheric electric fields (AEFs) generated by thunderstorms transfer energy to free

electrons, accelerate them, and, under certain conditions, induce electron-photon

avalanches. In 1992, Gurevich, Milikh, and Roussel-Dupré identified the conditions

necessary for extensive multiplication of electrons from each energetic seed electron

injected into a strong AEF region (Gurevich et al., 1992). This process is known as the

Relativistic Runaway Electron Avalanche (RREA; Babich et al., 2001; Alexeenko et al.,

2002). A numerical approach for solving the relativistic Boltzmann equation for runaway

electron beams (Symbalisty et al., 1998) aids in estimating the threshold AEF (Babich et

al., 2001; Dwyer et al., 2003) required to trigger RREA. As demonstrated by GEANT4

and CORSIKA simulations (Chilingarian et al., 2012, 2022), the RREA process is a

threshold phenomenon, with avalanches initiating when the atmospheric AEF exceeds a

certain threshold, which depends on the air density. The AEF must also be sufficiently

extended to support the growth of avalanches. At standard temperature and pressure in

dry air at sea level, Eth ≈ 2.80 \* n kV/cm, where air density n is relative to the

International Standard Atmosphere (ISA) sea-level value (see the recent update of the

threshold energy Eth ≈ 2.67 \* n kV/cm in Dwyer and Rassoul, 2024).

This threshold field is slightly higher than the breakeven field, which corresponds to the

electron energy at which minimum ionization occurs. If electrons traveled exactly along

AEF lines, it would define the threshold for runaway electron propagation and the start of

avalanche formation. However, the paths of electrons deviate due to Coulomb scattering

with atomic nuclei and Møller scattering with atomic electrons, causing deviations from

the near-vertical AEF. Additionally, secondary electrons produced by Møller scattering are

not generated along the field line; therefore, atmospheric electric fields must exceed

the theoretical RREA threshold Eth by approximately 10–20% for electrons to run away

and trigger an avalanche.

**1. CORSIKA simulations of RREAs reaching on Aragats stations**

To understand how avalanches develop in an electrified atmosphere and to compare the

new and updated Eth with the particle intensity growth, we used the CORSIKA code

(Heck et al., 1998), version 7400, which takes into account the effect of AEFs on particle

transport (Buitink et al., 2009). The growth of RREA definitely increases the cloud‘s

electrical conductivity. Numerous studies (Marshall et al., 1995; Stolzenburg et al., 2007)

have indicated that lightning flashes occur after the RREA threshold exceeds 20-30%.

RREA simulation codes do not include a lightning initiation mechanism. Therefore, one

can artificially raise the AEF strength beyond a realistic value to produce billions of

avalanche particles; however, this approach lacks physical justification. As a result, we

do not test AEFs stronger than 2.2 kV/m at altitudes of 3-6 km. The RREA simulation

was performed for vertical seed electrons with a uniform AEF that exceeded the Eth by a

few tens of percent. An introduced fixed uniform AEF shifts the surplus to Eth at different

heights by different percent, corresponding to air density. The seed electron energy

spectrum was based on the EXPACS WEB calculator (Sato, 2018), following a power

law with an index of 1.173 for energies from 1 to 300 MeV. During TGE events on

Aragats, the typical distance to the cloud base is estimated to be 25–200 m (see Fig. 17 in

Chilingarian et al., 2020); therefore, in our simulations, particle propagation continued in

dense air for an additional 25, 50, 100, and 200 meters before detection. The simulations

included 1,000 to 10,000 events for AEF strengths from 1.55 to 2.5 kV/cm. Electron and

gamma-ray propagation were tracked until their energies dropped to 0.05 MeV. The CORSIKA

code models the development of RREA by calculating the number of electrons and gamma rays at

different stages of the atmospheric electric field at 200-meter intervals.

Besides the Aragats and Nor Amberd research stations on the slopes of Mt. Aragats in

Armenia, we also conducted simulations for Slovakian and Chinese research stations at

Lomnický Štít and the Tibetan plateau. LHAASO (Large High Altitude Air Shower

Observatory) is situated at 4410 meters above sea level. It provides an ideal platform for

studying atmospheric particle acceleration due to its thin atmosphere and high likelihood

of runaway electron avalanche formation. We present CORSIKA simulation results

showing increases in electron and photon fluxes under AEF strengths ranging from 1.55

to 1.9 kV/m. The number of electrons and photons was recorded at depths ranging from

6510 meters to 4510 meters.

Lomnický Štít is located at an altitude of 2630 meters in Slovakia. CORSIKA simulations

were performed for various vertical AEFs ranging from 1.9 to 2.3 kV/cm. The number of

electrons and photons was recorded at depths ranging from 4734 meters to 2734 meters.

Significant increases in flux were observed with stronger **than threshold** fields, confirming the

development of robust RREA. Saturation trends in the growth of electrons and photons

suggest that the threshold field, Eth, at Lomnický Štít is approximately 2.3 kV/cm. These

results support earlier findings from Aragats and Nor Amberd and emphasize the altitude

dependence of Eth. Due to the thinner air at LHAASO, the TGEs occurred at a much lower

value of 1.7 kV/cm.

In Figures 1-4, we display the development of RREA at different atmospheric

depths and for various physically justified strengths of the AEF. The curves are scaled for

a single seed electron for easier comparison with experimentally measured intensities.

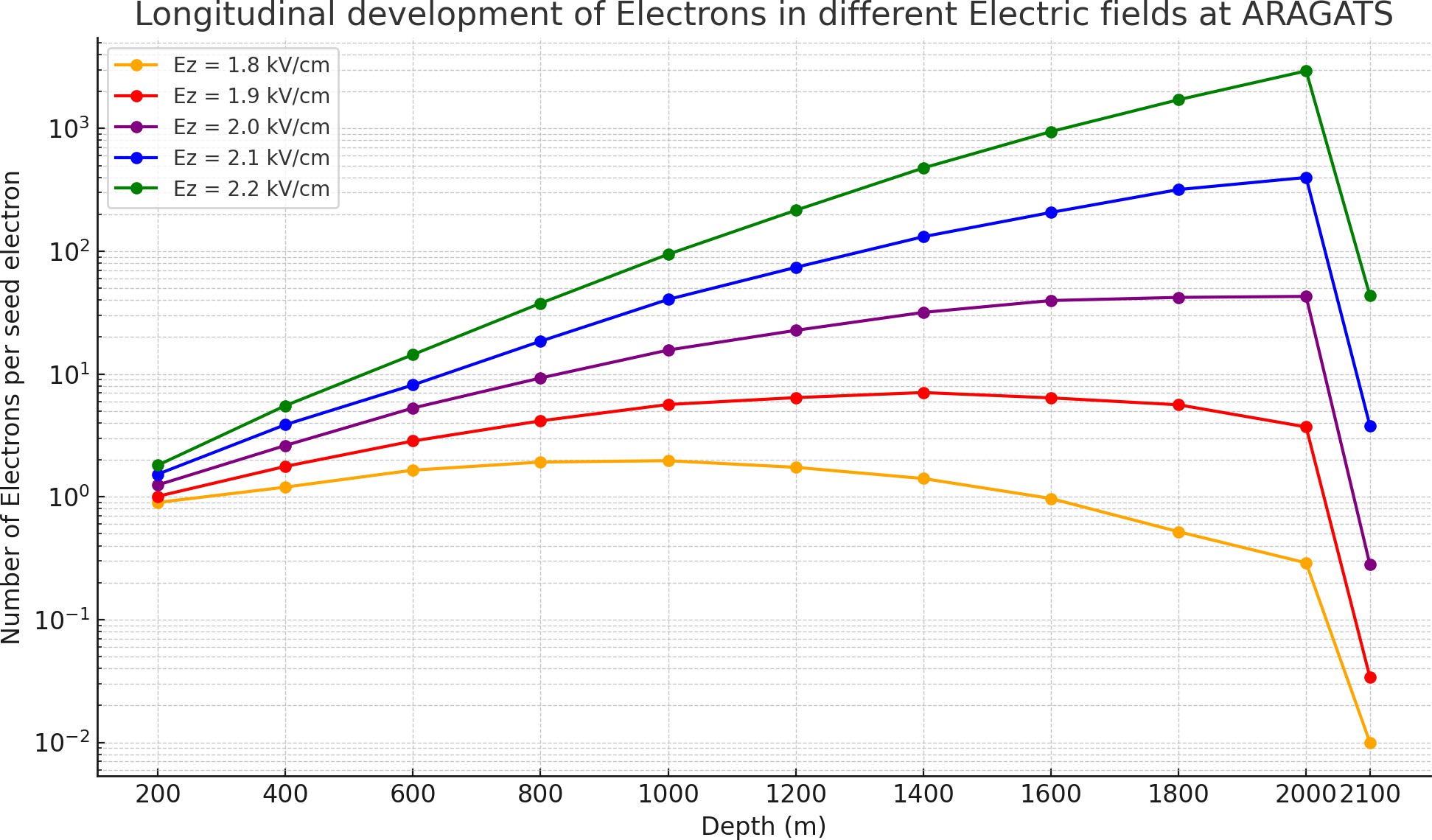
For each lower value of AEF, we observe saturation of the particle flux; the RREA process

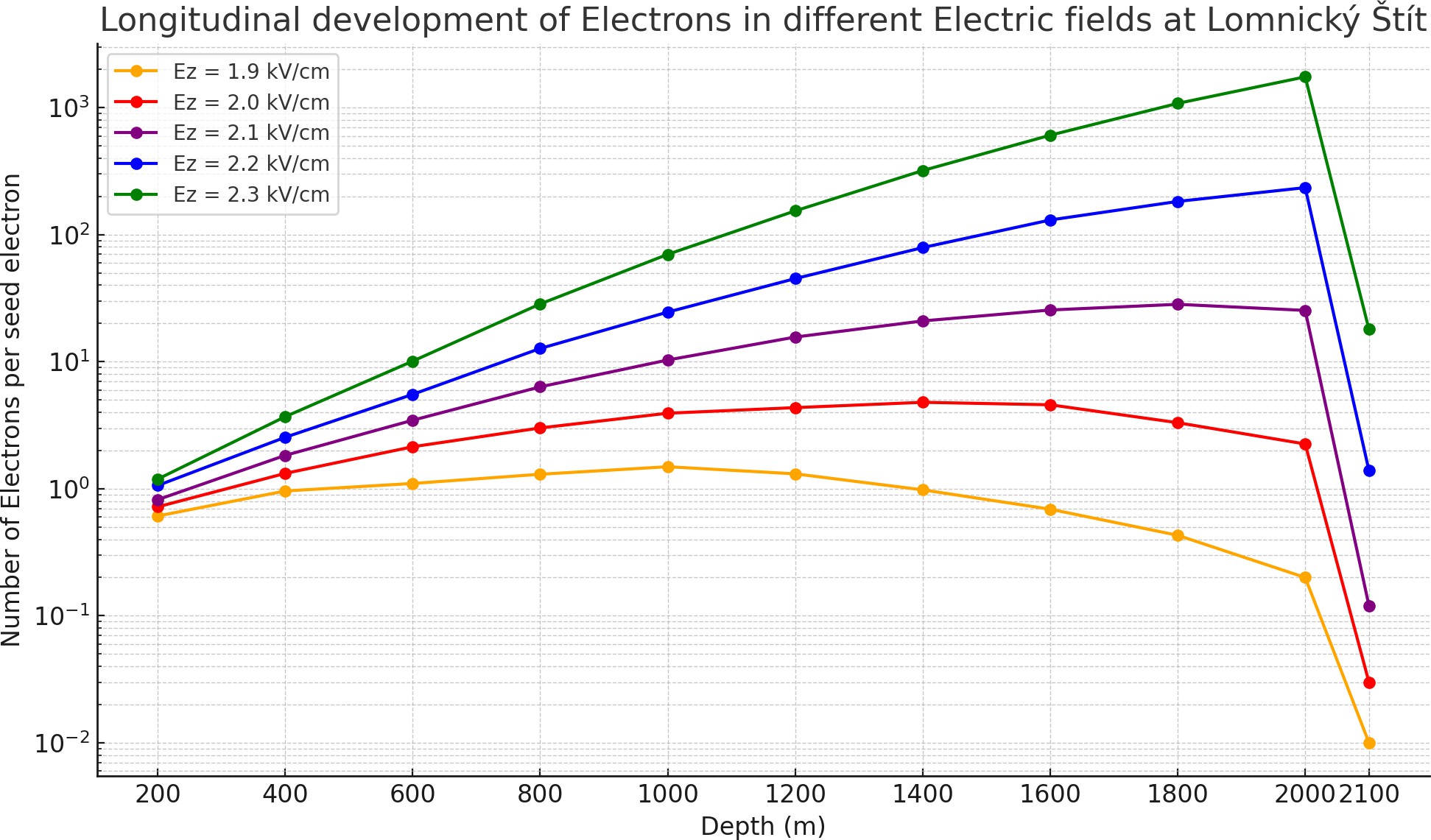
attenuates before reaching the observation level (see the red and yellow curves in Figs. 1-4).

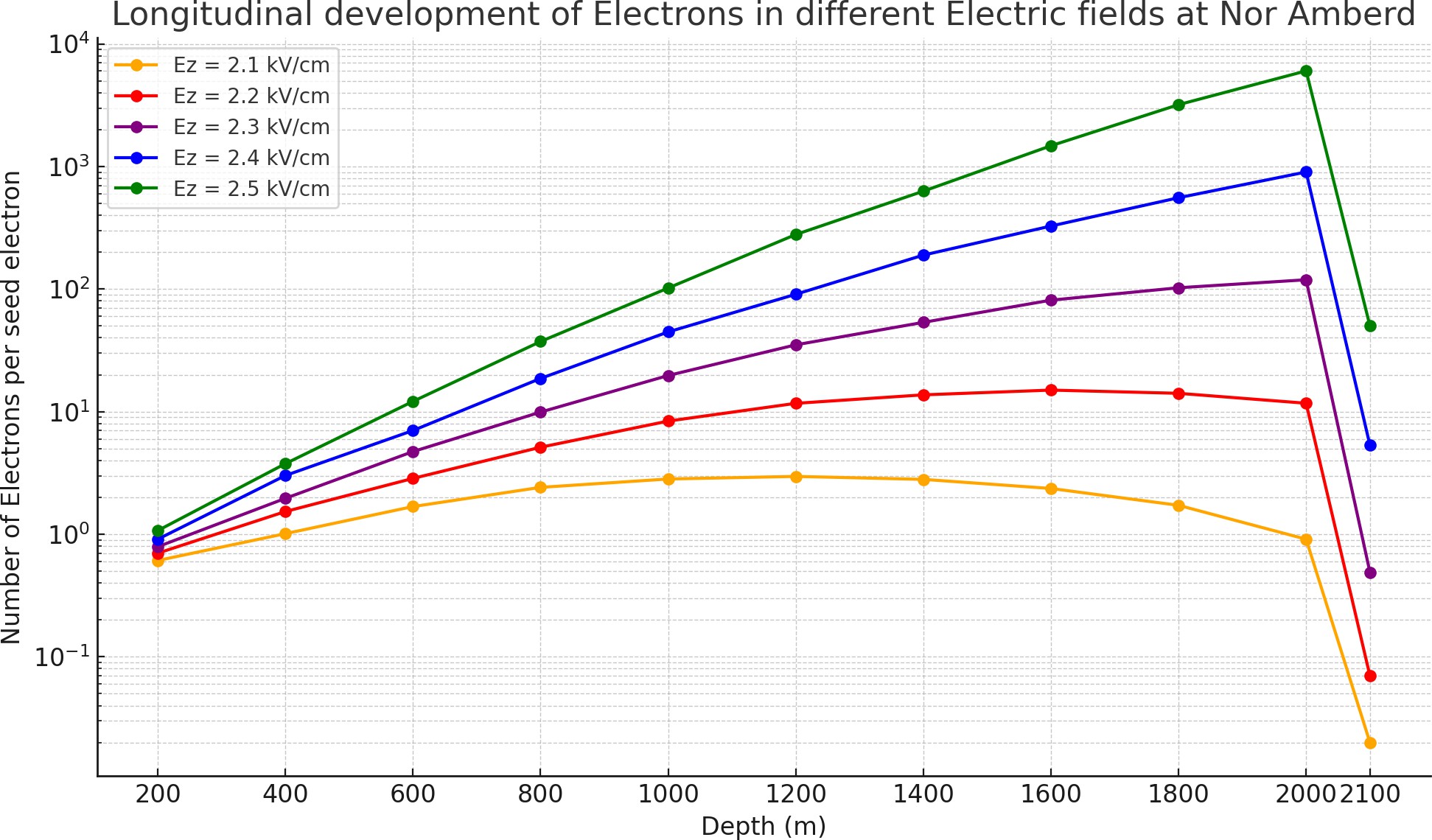
The smoother behavior of the photon curves is due to bremsstrahlung production, which averages

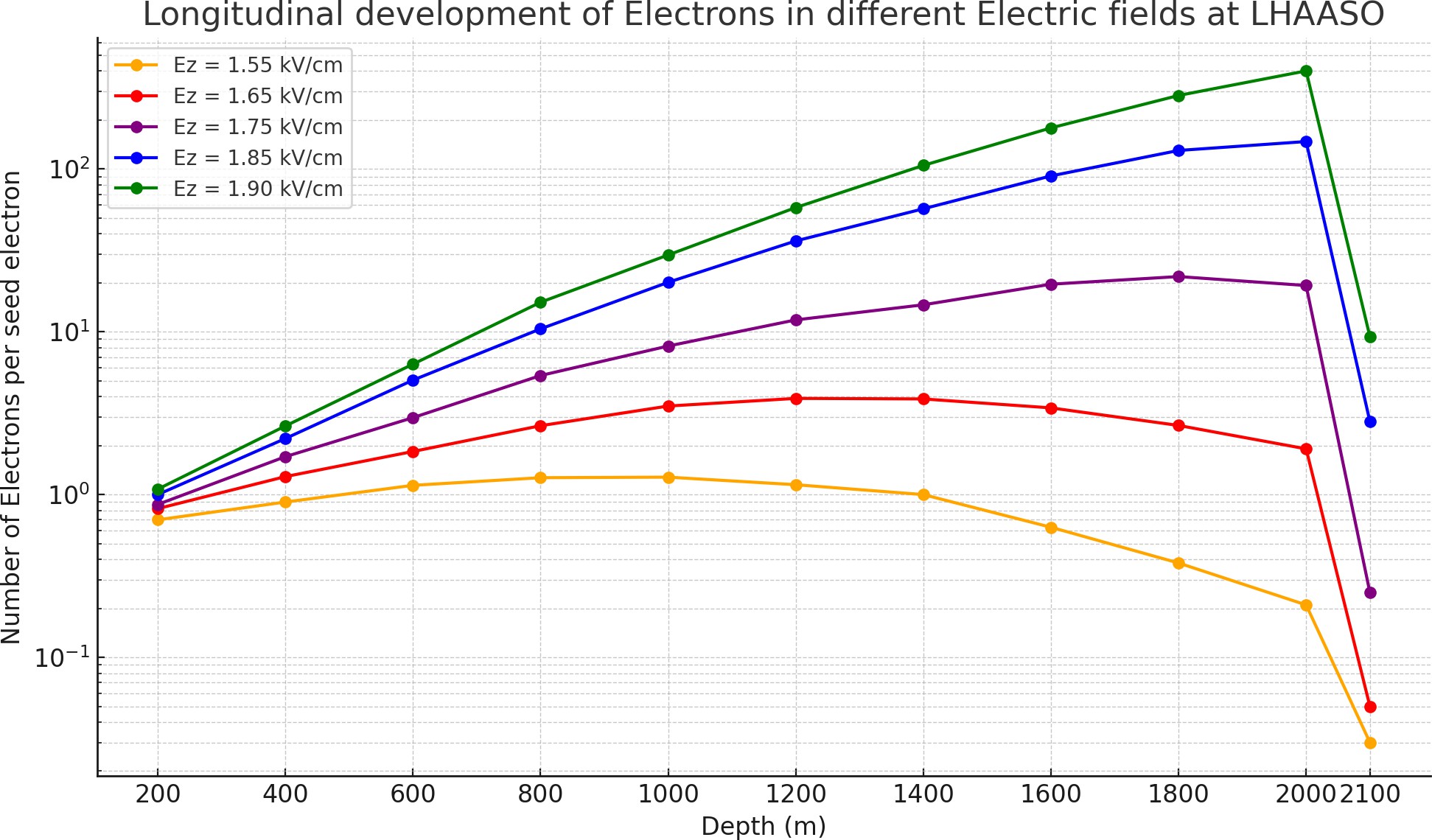
over a large number of electron interactions and therefore exhibits much smaller statistical

fluctuations compared to the electron curves.

**Figure 1: *Development of the RREA in the atmosphere. The avalanche started at 5400 meters above sea level, which is 2100 meters higher than the Aragats station. The number of avalanche particles is calculated every 200 meters. After leaving the AEF, the movement of avalanche particles is tracked for an additional 100 meters before reaching the station.***

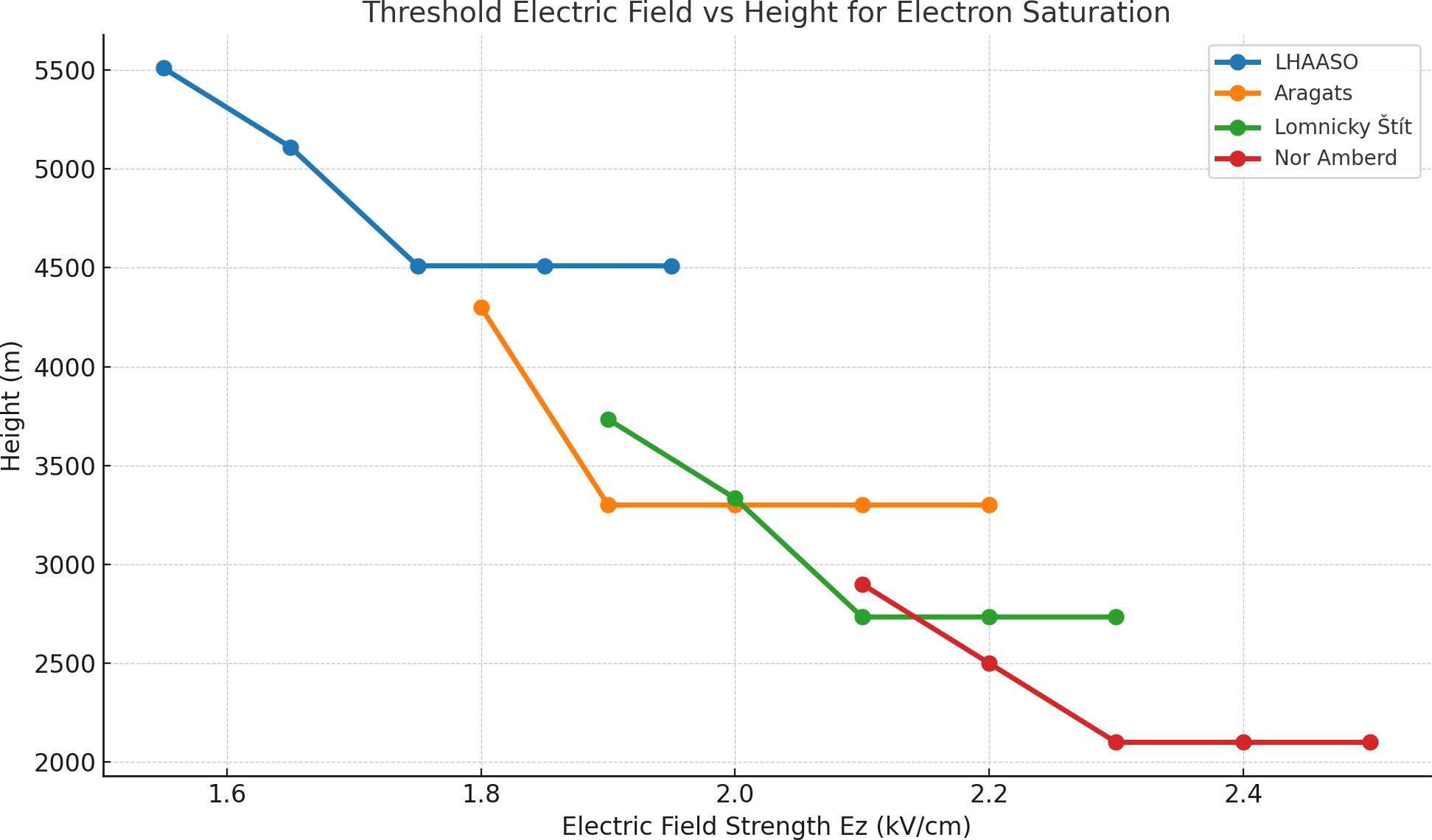
Figure 2: ***Same as Fig. 1, but for an avalanche initiated at 4730 m above the Lomnický Štít station.***

Figure 3: ***Same as Fig. 1, but for an avalanche initiated at 4100 m above the Nor Amberd station.***

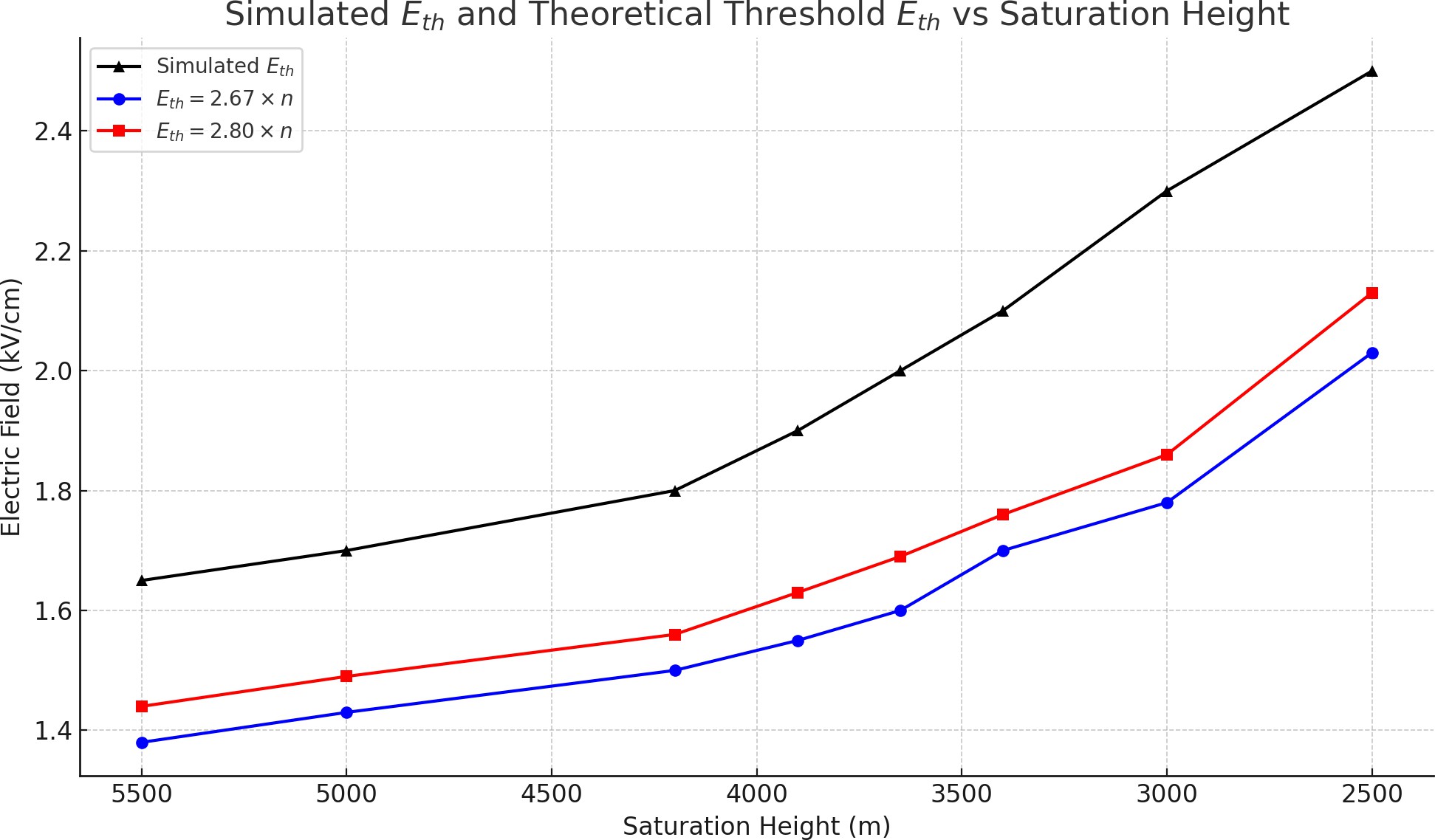
Figure 4: **Same as Fig. 1, but for an avalanche initiated at 6510 m above the LHAASO station.**

We estimate the “simulated” thresholds, Ez values, at the heights at which the amount of

avalanche particles stops rising, as shown in Fig. 5.

**Figure 5: The electric field strengths (Eth) at the point when the RREA particle flux began to decline for 4 stations located at altitudes ranging from 2000 to 4100 meters**.

In Figure 6 and Table 1, we compare the “simulated” threshold Ez with the theoretical ones. Simulations show higher values than theoretical estimates, especially for high Eth values (low altitudes) at all four research stations. The relative air density n is calculated using an exponential atmospheric model. Threshold fields are computed as 2.67 × n and 2.80 × n, representing the updated and theoretical thresholds, respectively. The percentage of enhancement indicates how much the applied field exceeds the theoretical thresholds. Strong AEFs, where the cascade did not attenuate, were not included in the table.

**Figure 6: The dependence of the heights in the atmosphere and the corresponding threshold AEF to start RREA for theoretical and simulated values**.

**Table 1. Excess of Ez over Eth. Stopping altitudes and theoretical threshold field comparisons for**

**heights 2500- 5550 m.**

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Input Ez | Enhancement | n | 2.67 × n | 2.80 × n | Rel. | Rel. | Site |
| (kV/cm) | Stops at h(m) | (relative | (kV/cm) | (kV/cm) | Excess. | Excess. |  |
|  |  | density) |  |  | (%) | (%) |  |
|  |  |  |  |  | (2.80) | (2.67) |  |
| 1.55 | 5510 | 0.465 | 1.24 | 1.30 | 19.0 | 24.8 | LHAASO  (4400 m) |
| 1.65 | 5110 | 0.492 | 1.31 | 1.38 | 19.8 | 25.7 | LHAASO  (4400 m) |
| 1.8 | 4200.0 | 0.558 | 1.49 | 1.56 | 15.2 | 20.8 | Aragats  (3200 m) |
| 1.9 | 3900.0 | 0.582 | 1.55 | 1.63 | 16.6 | 22.3 | Aragats (3200 m) |
| 1.9 | 3734 | 0.595 | 1.59 | 1.67 | 14.0 | 19.5 | Lomnicky Štít (2630  m) |
| 2.0 | 3334 | 0.629 | 1.68 | 1.76 | 13.5 | 19.0 | Lomnicky  Štít (2630 m) |
| 2.1 | 2700.0 | 0.687 | 1.84 | 1.92 | 9.1 | 14.4 | Nor  Amberd (2000 m) |
| 2.2 | 2500.0 | 0.707 | 1.89 | 1.98 | 11.2 | 16.6 | Nor Amberd  (2000 m) |

**2. Discussion and conclusion**

Although both the classical threshold field (Eth ≈ 2.80 × n kV/cm) and its updated

version (Eth ≈ 2.67 × n kV/cm) are derived under idealized assumptions, the difference

between them results from refinements in modeling particle energy loss processes. The

earlier estimate of 2.80 × n was based on basic energy balance considerations using older

ionization loss models and assumed monoenergetic electrons. This threshold is slightly

above the breakeven field, where energy gain equals average energy loss. The updated

2.67 × n value, introduced by Dwyer and Rassoul (2024), incorporates more accurate

relativistic Boltzmann solutions, improved ionization and bremsstrahlung cross-sections,

and a probabilistic treatment of runaway thresholds across realistic energy spectra. While

both thresholds assume idealized, field-aligned electron motion in a uniform medium, the

updated value is physically more consistent. It predicts a slightly lower field strength

needed for initial runaway. However, CORSIKA simulations show that this refined

threshold is insufficient for sustained avalanche growth under real atmospheric conditions

due to scattering and finite path effects. Moreover, it deviates more from the simulated

value than the “classical” 30-year-old estimate.

Multiple physical processes act to inhibit ideal runaway propagation. Coulomb scattering

with atmospheric nuclei and Møller scattering with electrons cause substantial angular

deflection and energy redistribution. Secondary electrons are not generated strictly along

the field direction, and many lose energy before gaining sufficient momentum to continue

avalanche growth. As a result, electrons must be accelerated in stronger-than-threshold

fields to overcome these losses and maintain avalanche conditions.

CORSIKA simulations, which incorporate all major interaction mechanisms—including

Coulomb and Møller scattering, bremsstrahlung losses, finite propagation distances, and

realistic secondary cosmic ray spectra—demonstrate that avalanches only fully develop

when the applied field exceeds the theoretical threshold by a measurable margin. For the

updated 2.67 × n value, we observe a required excess of approximately 20-22% at the

Aragats station (∼3200–4200 m a.s.l.), whereas for the classical 2.80 × n threshold, the

excess is typically 15-17%.

Interestingly, this required excess decreases with increasing air density, as observed in

the Nor Amberd simulations. At lower altitudes (∼2500–2700 m a.s.l.), the difference

between the applied and threshold fields is reduced: only 14–16% above 2.67 × n, and

about 9–11% above 2.80 × n. This trend can be explained as follows:

In denser air, the chances of energy loss interactions increase, but so does the likelihood

of electron multiplication through ionization and bremsstrahlung over shorter distances.

The avalanche can develop more quickly because seed electrons encounter more target

atoms in a given path length. As a result, the necessary “headroom” above the threshold

field for sustained multiplication is smaller. Simply put, the efficiency of avalanche

formation improves in denser air, even though the absolute threshold field is higher. This

results in a smaller relative excess being required above the theoretical threshold.

Therefore, although the threshold field scales linearly with air density, the required

enhancement factor does not. It decreases with increasing density due to a balance

between energy loss and multiplication processes, all of which are faithfully captured in

the CORSIKA simulation framework. This emphasizes the importance of altitude-dependent

analysis in interpreting Thunderstorm Ground Enhancements (TGEs) and

suggests that scaling laws based solely on density may overlook subtler effects arising

from atmospheric structure and shower development dynamics.

**Code and data availability**

Data archive on TGE event is reposted on the Mendelay site at

https://doi.org/10.17632/8gtdbch59z (Chilingarian et al., 2024).

Data archive on CORSIKA simulations (RREA development in the atmosphere above 4

sites) is available at the link:

<http://crd.yerphi.am/CORSIKA_Simulations>

**Author contribution**

AC and MZ designed the simulation experiments with the CORSIKA code, and LH

performed the simulations. AC prepared the manuscript with contributions from all co-

authors

**Acknowledgment**

The authors acknowledge the support of the Science Committee of the Republic of

Armenia (Research Project No. 21AG֊1C012) 231

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